NASA CR-177,987

NASA Contractor Report 177987

NASA-CR-177987
19860003142

ADVANCED TORQUE CONVERTERS FOR ROBOTICS AND SPACE APPLICATIONS

TALANDIC RESEARCH CORPORATION
Pasadena, California

Contract NAS1-17938
July 1985

National Aeronautics and
Space Administration

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ABSTRACT

This report covers the technical effort performed as part of a NASA SBIR Phase I contract to Talandic Research Corporation (TRC). The entire effort was intended to exploit a novel torque converter invented by Ahmad Amjadi, for which a U.S. patent has been granted. The Phase I work consisted of design, fabrication and test of two working models of the Amjadi Transmission as well as theoretical analysis to determine the limits of performance. Major emphasis of the Phase I work was on tool drivers.

Two functioning units were designed and fabricated. The first unit consisted of five phases and the input and output shafts were parallel but not collinear. This model was used primarily for quantitative analysis of the operating characteristics of the device. In addition, a collinear model was constructed in a compact housing suited for a handheld tool application. These models allowed us to verify the most interesting features of the basic concept. These features are as follows:

a. Automatic and rapid adjustment of the effective "gear ratio" in response to changes in the external torque requirements.

b. Maintenance of the output torque on the load even at zero output velocity, without loading the input power source.

c. Excellent isolation of input power source from the load even though they were direct machanically coupled.

It was also found that the devices are apparently suited to certain types of tool driver applications, such as screwdrivers, nut drivers, and valve actuators, among others, as originally proposed. Robotics applications were evaluated and it was found that, while there are many potential applications for this torque converter that must still be explored, its use for robotic actuators does not appear to provide sufficient advantages to warrant serious consideration. The models developed for this program allowed us to make a qualitative determination of basic device properties. However, we were unable to obtain sufficient quantitative information to draw final conclusions as to the commercial viability of this device in tools and robotics applications.

1.Ø INTRODUCTION

This report covers the technical effort performed as part of a NASA SBIR Phase I contract to Talandic Research Corporation (TRC). The entire effort was intended to exploit a novel torque converter invented by Ahmad Amjadi, for which a U.S. Patent (#4,188,831) has been granted. The Phase I work consisted of design, fabrication and test of two working models of the Amjadi Transmission as well as theoretical analysis to determine the limits of performance. Major emphasis of the Phase I work was on tool drivers.

The Amjadi transmission is a mechanical torque converter which is unique in its properties and is ideal for a wide range of power transmission applications. It is capable of transmitting torque to a load over a continuously variable range of output velocities and with very high energy efficiency because it is direct mechanically coupled. No fluids or dissipative clutches are employed. In addition, the drive ratio between the input and output shafts can be manually adjusted or, alternatively, the drive ratio can be automatically adjusted to suit the torque demands of the load, even to zero output shaft velocity. Input shaft velocity can be maintained constant over a wide range of output velocities so that the power source is utilized in its most efficient manner.

There is potential application of this device in vehicular, robotics and tool applications. It is the latter two which form the basis for this SBIR program. The property of maintaining maximum torque at zero output velocity and the ability to change drive ratios automatically suggests applications in robotics for lifting and gripping tasks and in power machinery where load varies widely. At zero output

velocity, there is effectively no power consumption and therefore, torque can be applied indefinitely with little input power consumption. Several different implementations of the basic concept are available depending on the application.

In what follows, we detail our findings and summarize our conclusions as to the suitability of the Amjadi Transmission for the intended applications. We will conclude below that there are many positive opportunities to apply the unique properties of the Amjadi Transmission to both tool drivers and to robotics. However, these conclusions are sufficiently preliminary that additional work is required to determine the commercial feasibility of this approach.

2.0 PROGRAM GOALS AND OVERVIEW OF ACCOMPLISHMENTS

The details of our technical approach and the work plan are extensively discussed in our Phase I proposal and will not be repeated here. The specific objectives of the Phase I research and development effort are summarized as follows:

1. To develop miniaturized and better optimized transmission modules based on the subject invention.

2. To implement the application of the transmission module to simple tools.

3. To explore the materials issues for rendering the device structures more rugged.

4. To investigate more efficient candidates for the mechanical "diodes" (or ratchets) which determine the direction of the energy coupling to the load.

5. To evaluate the prototype tool-drivers and assess feasibility of future Phase II and commercial developments.

6. To model the coupling modules in terms of dynamic range, energy efficiency, and other performance parameters and to compare these with experimental results.

The extent to which these objectives have been achieved is detailed in Sections 3, 4 and 5 below.

Early in the conduct of the work it was decided that the model used for testing would be a five-stage spring-coupled non-collinear device. This configuration appeared to be most suitable for construction of tool drivers and was simplest to modify for purposes of evaluation. Another model utilizing a collinear configuration with three phases was also constructed. This second model represented the most compact configuration from the point-of-view of packaging. We utilized coiled spring clutches for the unidirectional coupling mechanisms in both models. The details of these two models will be discussed in the following sections.

Our approach to the theoretical modeling was to construct a computer program to compute exact solutions for the transfer function of various configurations of the torque converter. Initial calculations, reported below, illustrate some of the basic features of the device. The model also includes provisions to incorporate real losses and imperfections in future calculations.

3.0 DEVICE MODELING

We have carried out modeling calculations to arrive at a better understanding of the operation of the Amjadi torque convertor for future design purposes. Although the basic device concept is relatively simple, detailed calculation of the operation of a multi-phase transmission turns out to be quite complex, particularly when kinetic and static frictional forces are taken into account. Still, much can be learned by examining some special cases. In this section, we report the results of some of the modeling calculations.

3.1 Single-Phase Device

We will analyze the case of a single-phase device in some detail and then summarize the extension to multi-phase devices.

3.1.1 Basic Principles

Referring to Fig. 3-1, we examine a motor shaft rotating at an angular velocity w_M which is directly coupled to the load shaft by a one-way clutch, shown schematically by an internal ratchet mechanism. Rotation of the motor shaft will tend to stretch the spring and apply a torque, T, to the load, as given by

$$\vec{T} = \vec{r_L} \times \vec{F} \quad , \qquad (1)$$

where r_L is the radius of the pivot point on the load shaft (point B in Fig. 3-1), and F is the force generated in the spring.

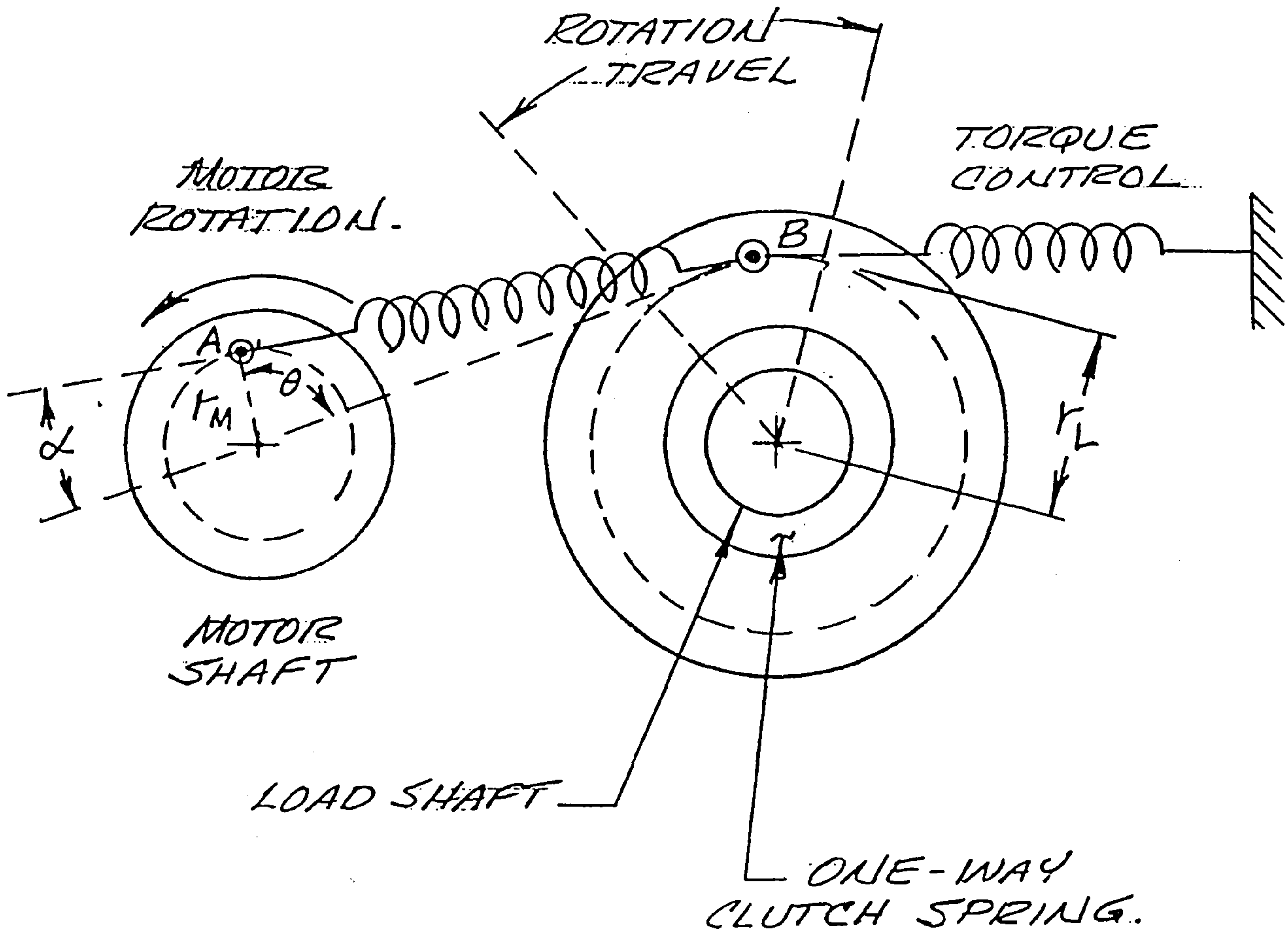

Figure 3-1 Schematic diagram of a single-phase Amjadi transmission. Vertical direction is used as a reference for the rotation angle of the motor shaft.

First, we will take the simplest case when the force needed to turn the load shaft (F_L) is larger than can be supplied by the spring, even when the spring is stretched to its maximum distance of $2r_M$. In this case, rotation of the motor shaft will cause a (quasi-) sinusoidal force on the spring. This force will become "rectified" by the diode and applied to the load shaft, as shown in Fig. 3-2.

Strictly speaking, the applied force is not a pure sinusoidal function of the angle θ or time. The stretching ΔL of the spring per unit rotation of point A is dependent on the angle θ, and the torque has some variations due to variations of the angle α :

$$\begin{aligned} \vec{T} &= \vec{r_L} \times \vec{F} \cdot \cos(\alpha) \\ &= \vec{r_L} \times \vec{K} \cdot \Delta L \cdot \cos(\alpha). \end{aligned} \quad (2)$$

It can be shown that

$$T = r_L K \cos(\alpha) \left\{ \left[r_M^2 + (L_o + r_M)^2 - 2r_M (r_M + L_o) \cos(\theta - \theta_o) \right]^{\frac{1}{2}} - L_o \right\} \quad (3)$$

where L_o and K are the unstretched length and the force constants of the spring, and other variables have been defined earlier (or in Figure 3-1). Motion of Point B adds additional complexity. Again, for simplicity, we will assume sinusoidal variations of ΔL, F_L, and T, since the effects qualitatively remain the same.

If we now allow the maximum spring force to be more than sufficient to turn the load, the spring will begin to stretch until the necessary force F_L is reached. At that time, if we ignore inertial effects, the spring no longer needs

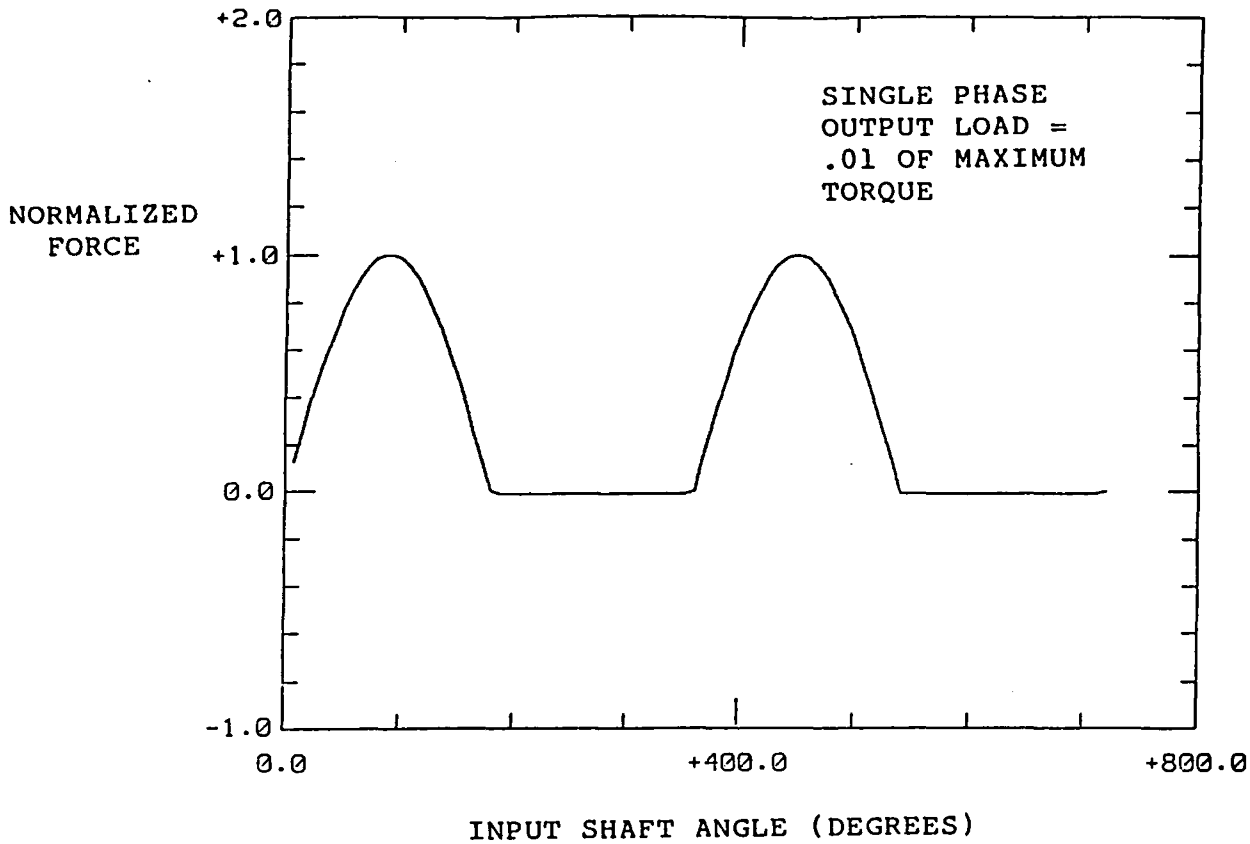

Figure 3-2 Normalized force applied to the load shaft of a single-phase device, as a function of the input shaft angle.

to stretch. Instead, it will move the pivot point B as if the spring were replaced by a rigid rod. Load rotation velocity will at once change from near zero to a maximum value given by

$$w_L = \frac{r_M}{r_L} \cdot w_M \tag{4}$$

Figs. 3-3(a) and 3-3(b) show how the load velocity, normalized to its value given in Equation 4, varies for different torque demands of the load. The periodic (pulsed) nature of this one-phase device is clearly seen. In a real device, the inertia of the load will significantly reduce the abruptness of the pulses, as well as lower the instantaneous peak values. Addition of more phases will also result in smoother operation.

Since no energy loss mechanism due to the use of fluids or frictional clutches are present, a well-built device should be very energy efficient. The energy not delivered to the load will go back to the motor in the second half of each cycle. Moreover, the pulsed nature of the operation may be a useful feature for some tool drivers, such as impact wrenches. The peak instantaneous torque will always be limited by the spring force constant and the values of r_M and r_L.

3.1.2 Torque and Velocity Control

For the device described above, the (instantaneous) power from the motor, P, is delivered to the load in such a way that the output velocity is always maximized for the amount of output torque required. Therefore, when torque requirements go down, output velocity increases automatically, and vice versa:

$$P = T \cdot w_L \ . \tag{5}$$

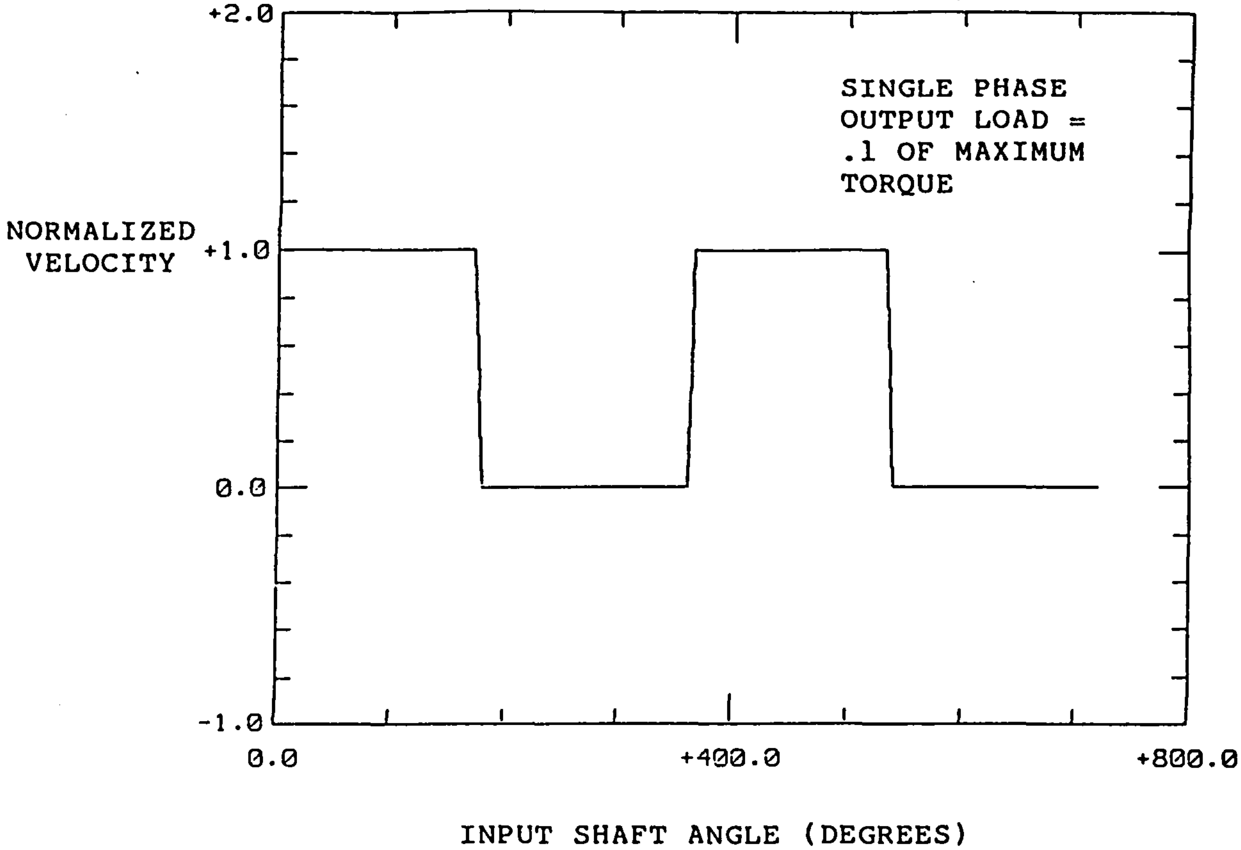

Figure 3-3(a) Normalized load velocity for a single-phase device, for load requirements of 10%.

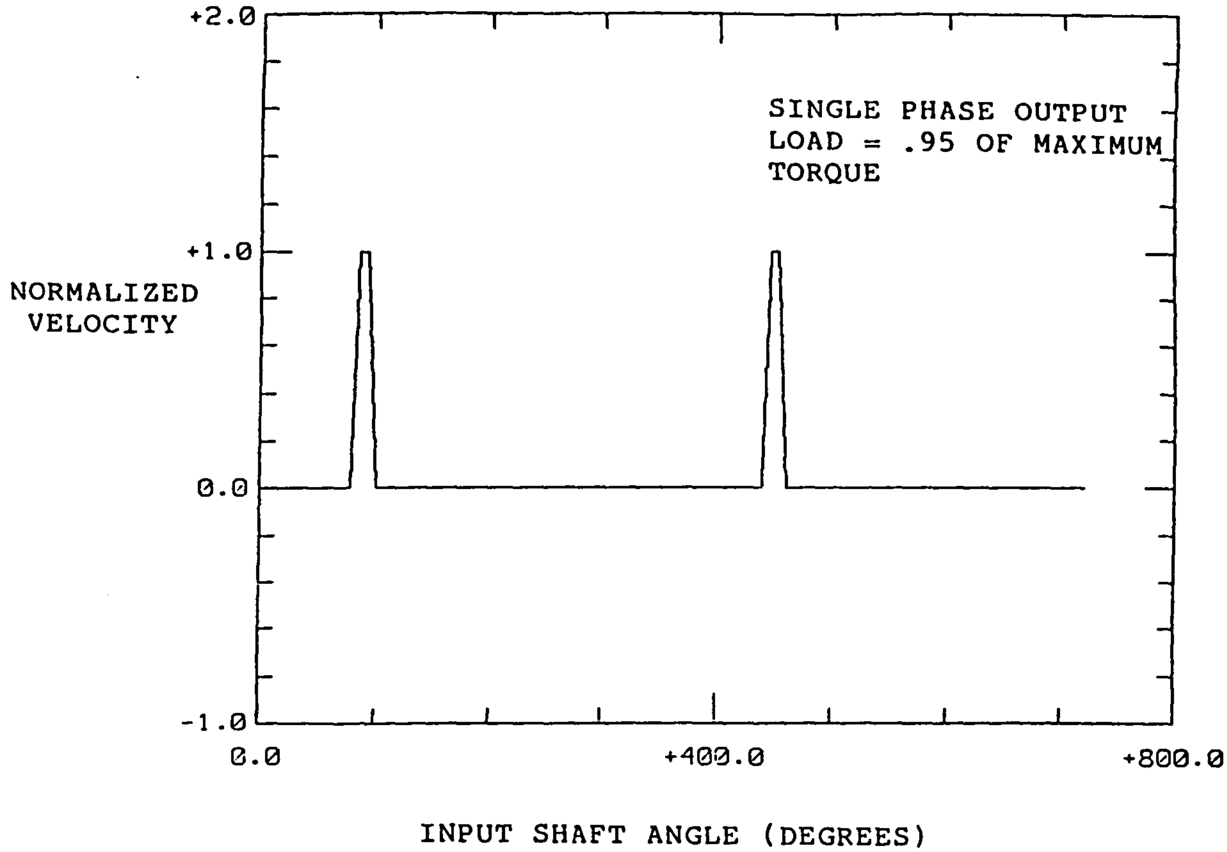

Figure 3-3(b) Normalized load velocity for a single-phase device, for load requirements of 95% of the maximum spring force.

Application of this type of transmission device as a tool driver may require the torque and output velocity to be adjustable individually, and not just determined automatically by Equation 5. Figure 3-4 shows a modified version of the one-phase device, having provisions for individual control of T and w_L. Here, the endpoint on spring K_2 can be adjusted so that K_2 can oppose to the desired extent the action of the main spring K_1. The torque felt by the Load at point B is the difference between these forces. Clearly, for this scheme to work, the driving force has to be able to exceed that of K_2.

The velocity control mechanism shown in Figure 3-4 operates by the stopping action of the spring K_3 on the motion of the clutch. If K_3 is chosen to be large, the driving force on the load will come to a more or less abrupt end. Beyond this point, and until the start of another rotation cycle, the load will artificially look unmovable to the motor. The energy stored in the spring K_1 will thus go back to the motor in the second half of each cycle. The average load velocity will become controlled by the location of the velocity control mechanism.

3.2 Multi-Phase Devices

Multi-phase power delivery to the load adds considerably to the smoothness of the operation, as can be seen in Figs. 3-5 through 3-7 for the normalized force (or torque) for 3-, 4-, and 5-phase devices. These curves are for the case of stalled load, i.e., the load cannot move under the maximum force available from the sum of the springs. As expected, having odd numbers of phases leads to smoother operation.

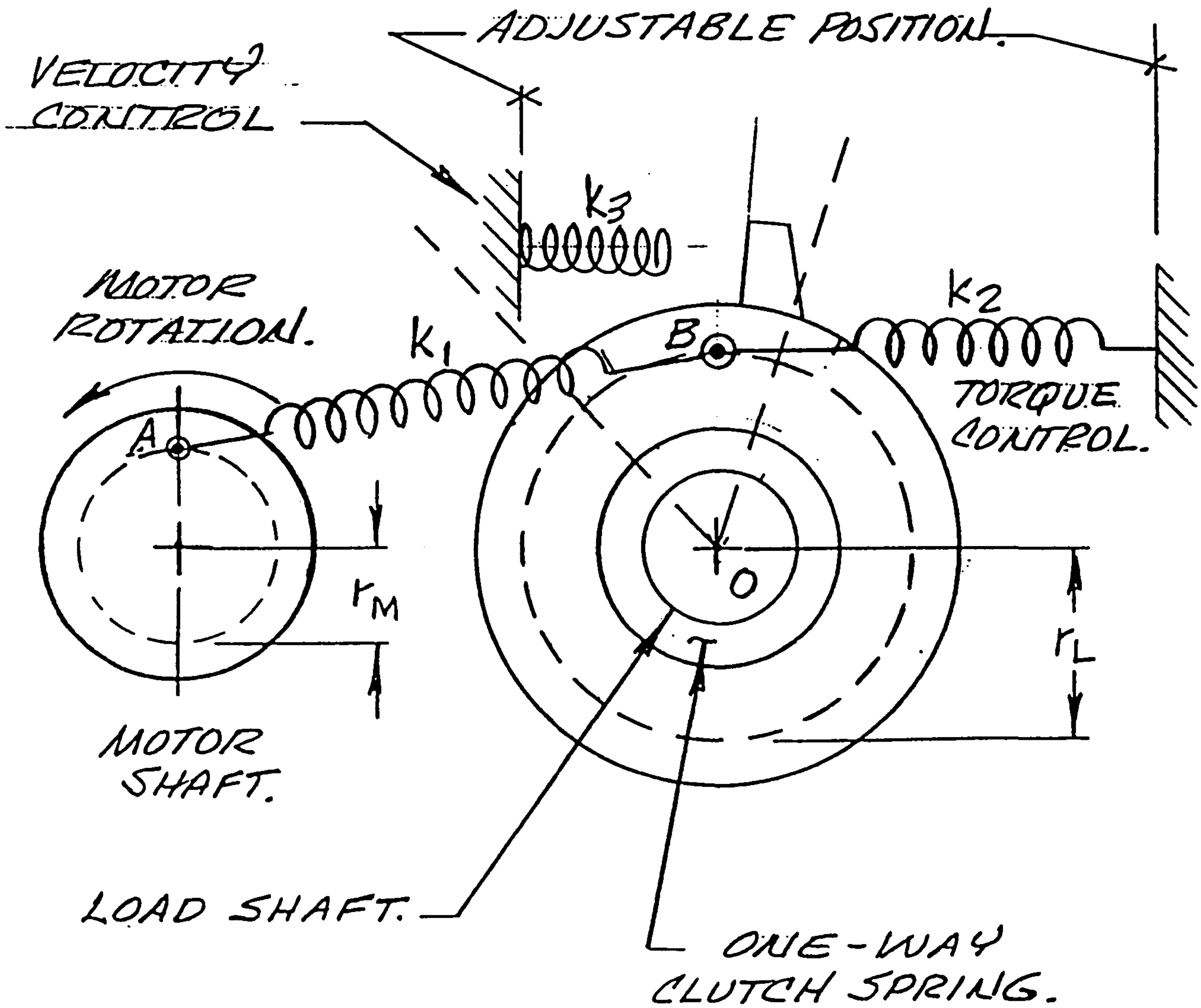

Figure 3-4 Schematic diagram of a modified single-phase device such that the output torque and output velocity may be controlled individually.

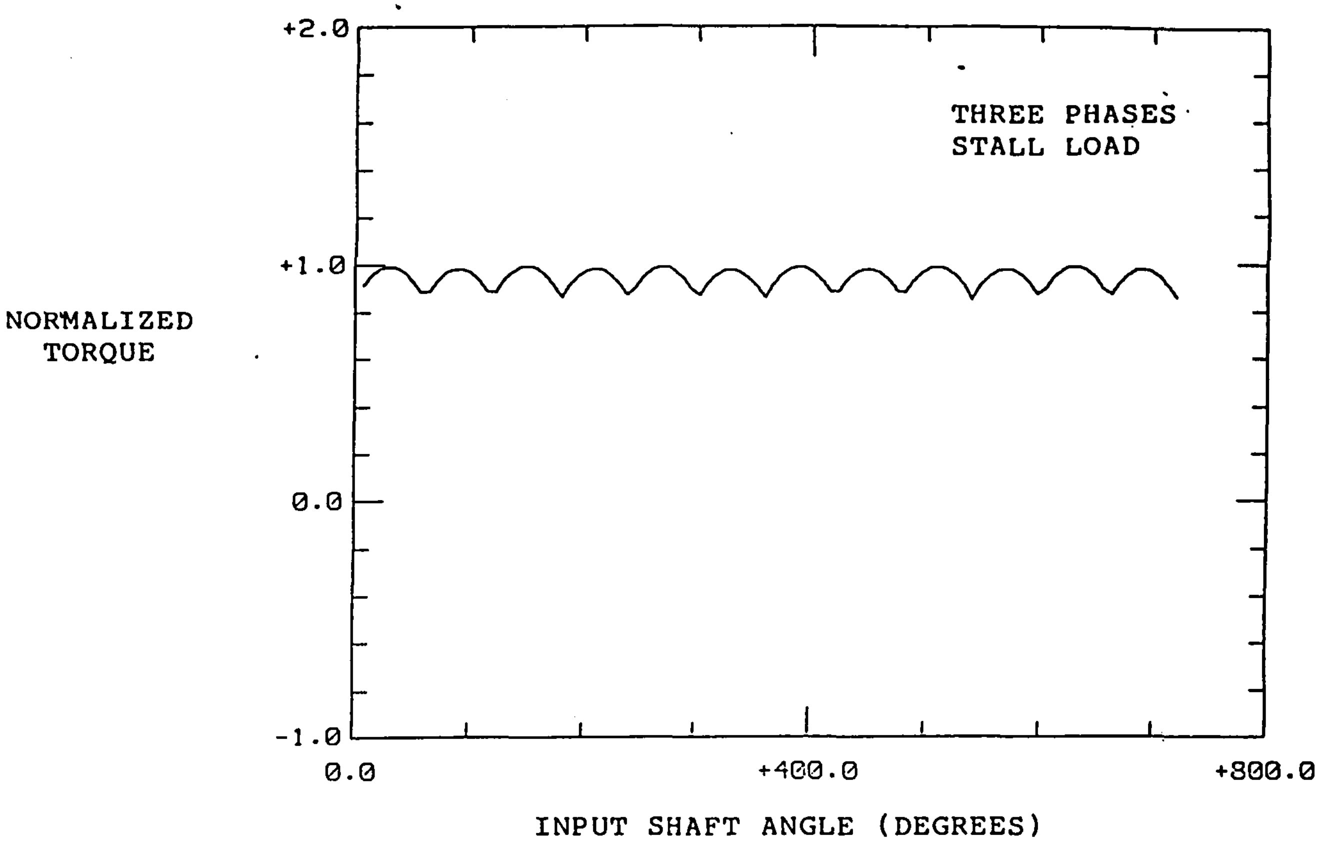

Figure 3-5 Normalized output force, or torque, for a 3-phase device. The curve is for the condition of stall.

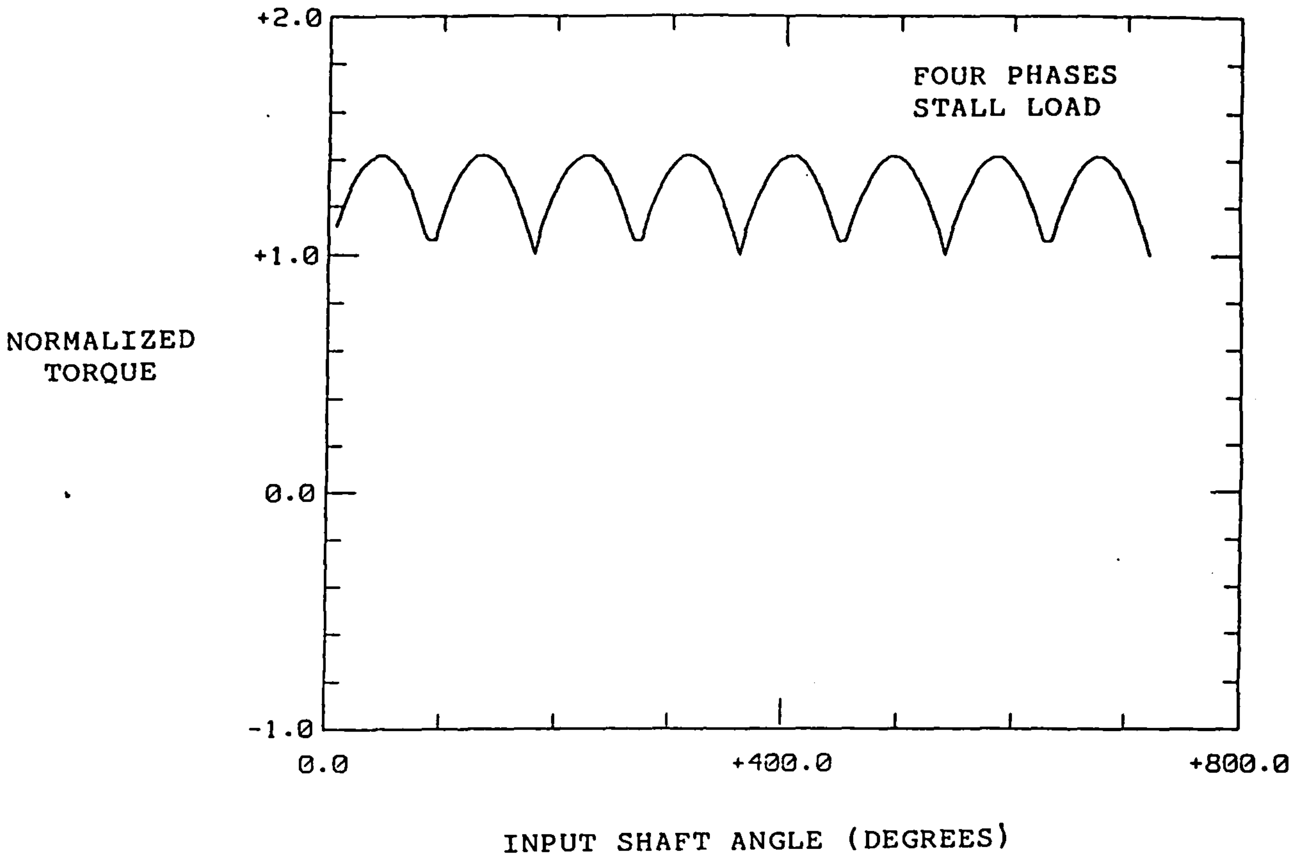

Figure 3-6 Normalized output for a 4-phase device at stall.

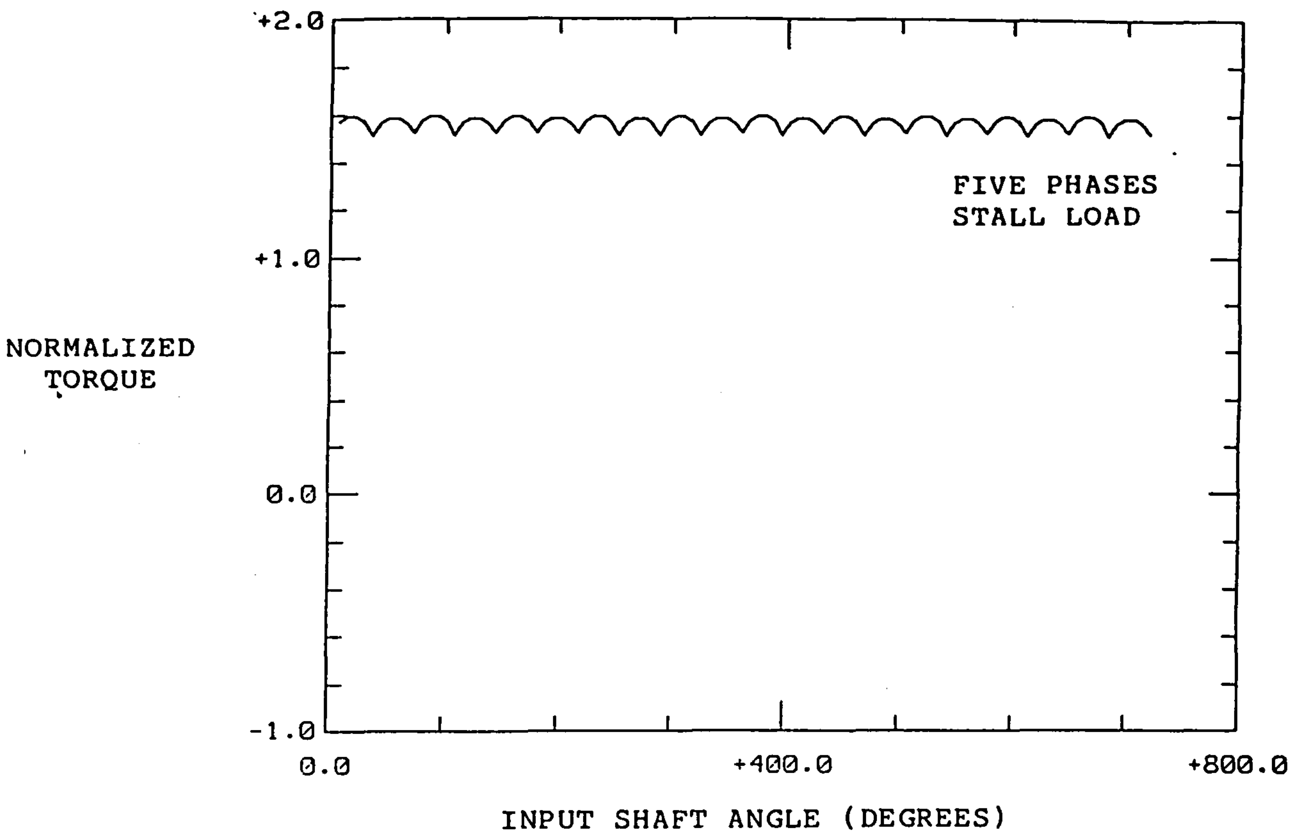

Figure 3-7 Normalized output for a 5-phase device at stall.

Figs. 3-8(a) and 3- 8(b) show the output velocity for a 3-phase device for output torque requirements of 50 percent and 99 percent of the maximum value that can be put out by one spring. Pulsed behavior is observed for high output torque demands. Again, a mass at the output will have a smoothing effect. At medium-to-low torque requirements (Fig. 3-8(a)), the speed is rather smooth. Figure 3-9 shows the output velocity for a 5-phase device at 99 percent of the stalling torque.

3.3 Output Characteristics

Examination of the output characteristics of a simple N-phase device can be modeled to yield the relationships between the output torque, velocity, and average power. If the force constant of each of the springs is K, then it can be shown that the load frequency f_L (in revolutions per second) is related to the motor frequency f_M by the following relation

$$f_L = f_M \quad \frac{2 r_M \overline{N}}{\pi r_L} - \frac{T_L}{2 \pi K \; r_L^2} \tag{6}$$

where $\overline{N}$ is the effective number of phases, and T_L is the maximum instantaneous torque applied to the load. Equation 6 gives a relationship for a load line which can be used for designing devices for particular specifications, or determining the expected load frequency as a function of the torque. An example of such a curve is shown in Fig. 3-10.

The effective number of phases $\overline{N}$ is related to the number of phases N. By integration of the area under the torque vs. angle (or time) curve, and comparing with a constant torque at the maximum value for one spring the effective number can be determined. To a good approximation,

$$\overline{N} = (0.32) N \tag{7}$$

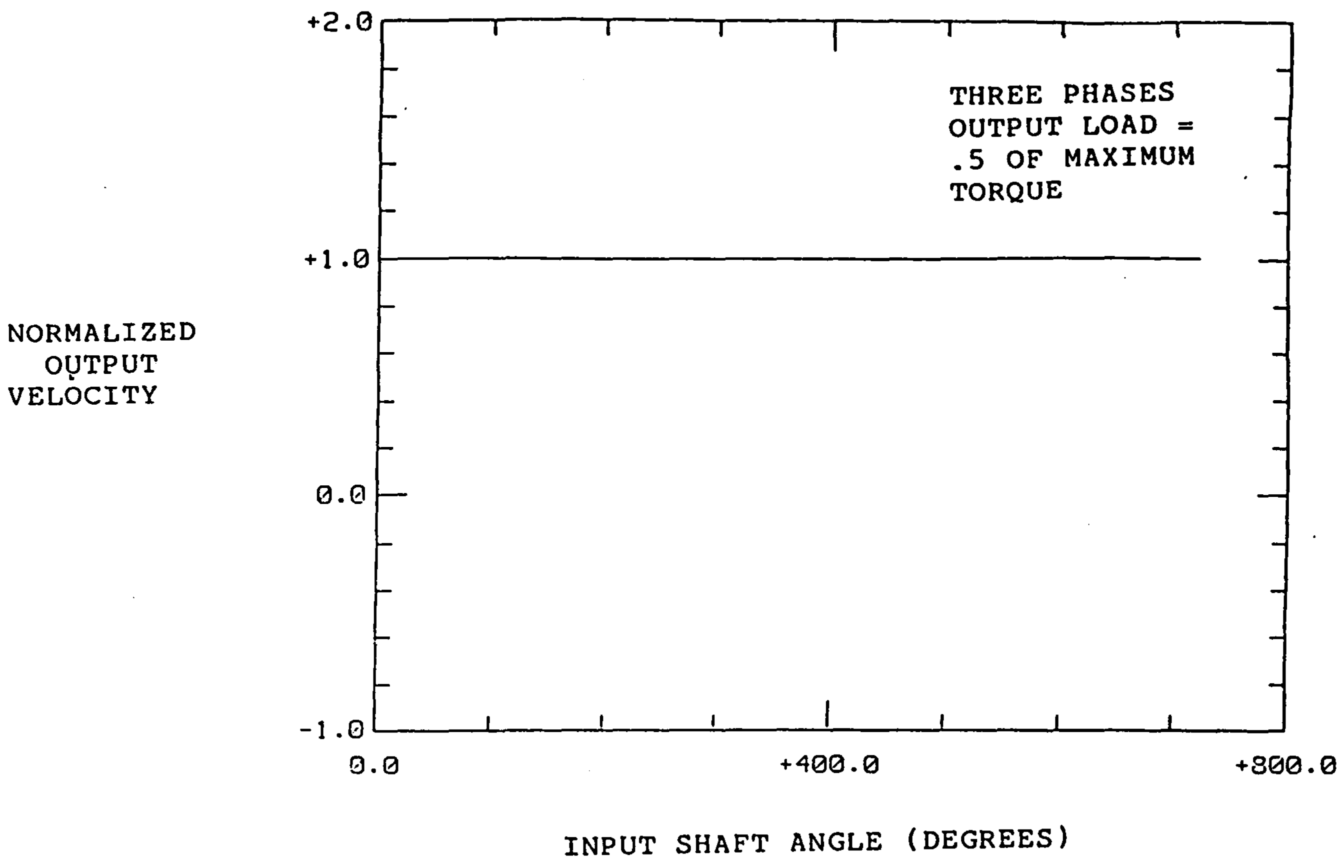

Figure 3-8(a) Normalized output velocity for a 3-phase device with the output torque requirements of 50%.

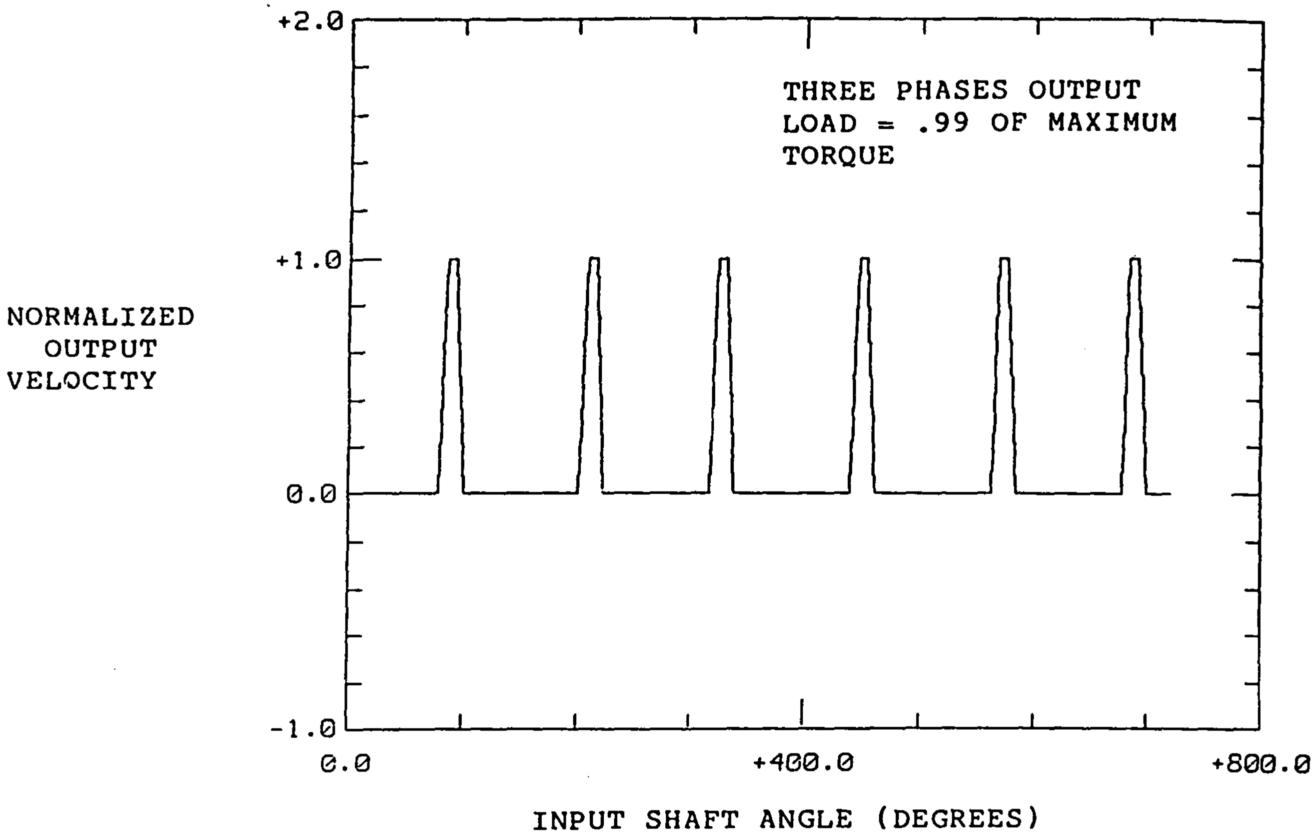

Figure 3-8(b) Normalized output velocity for a 3-phase device with the output torque requirements of 99% of the maximum (of one phase).

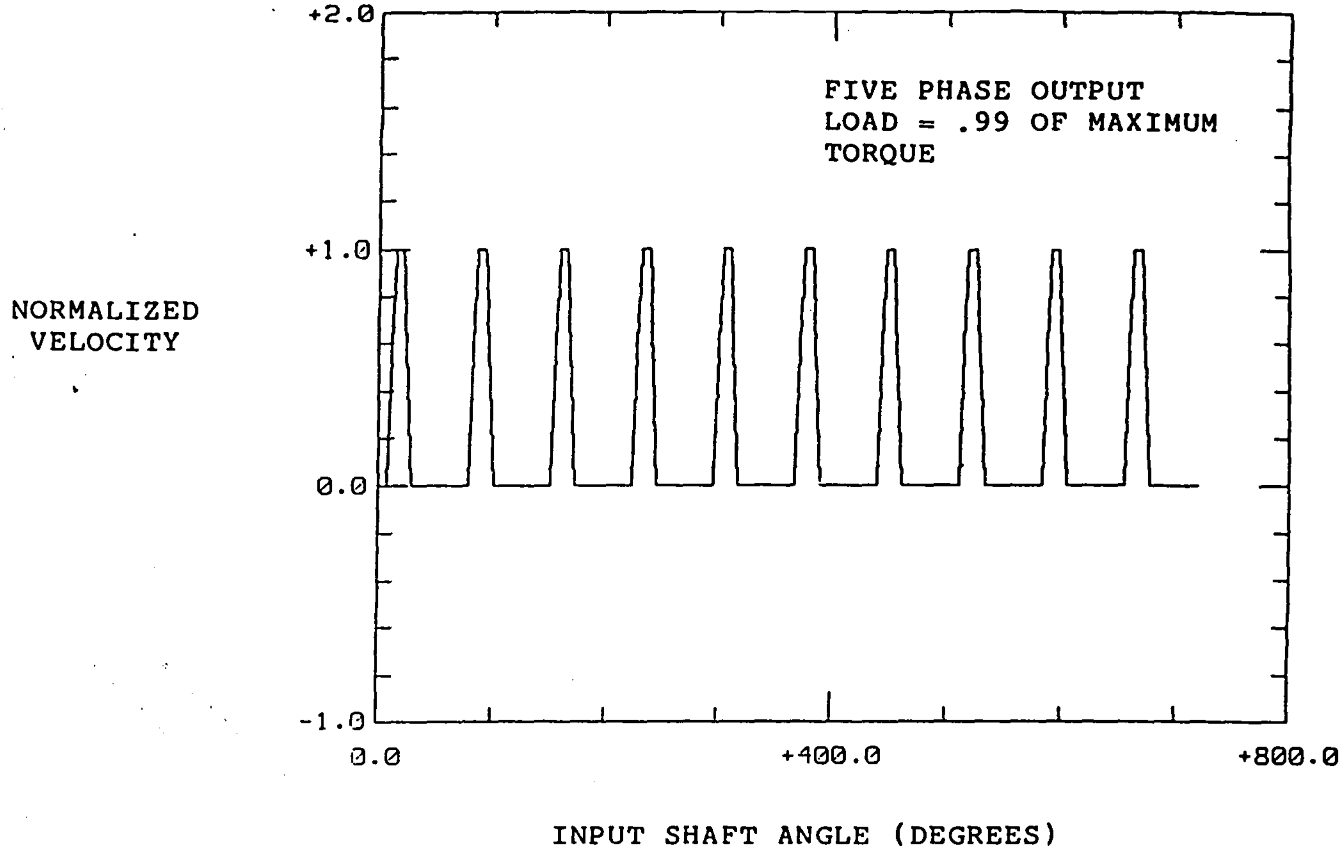

Figure 3-9 Normalized output velocity for a 5-phase device with the output requirements of 99% of the maximum.

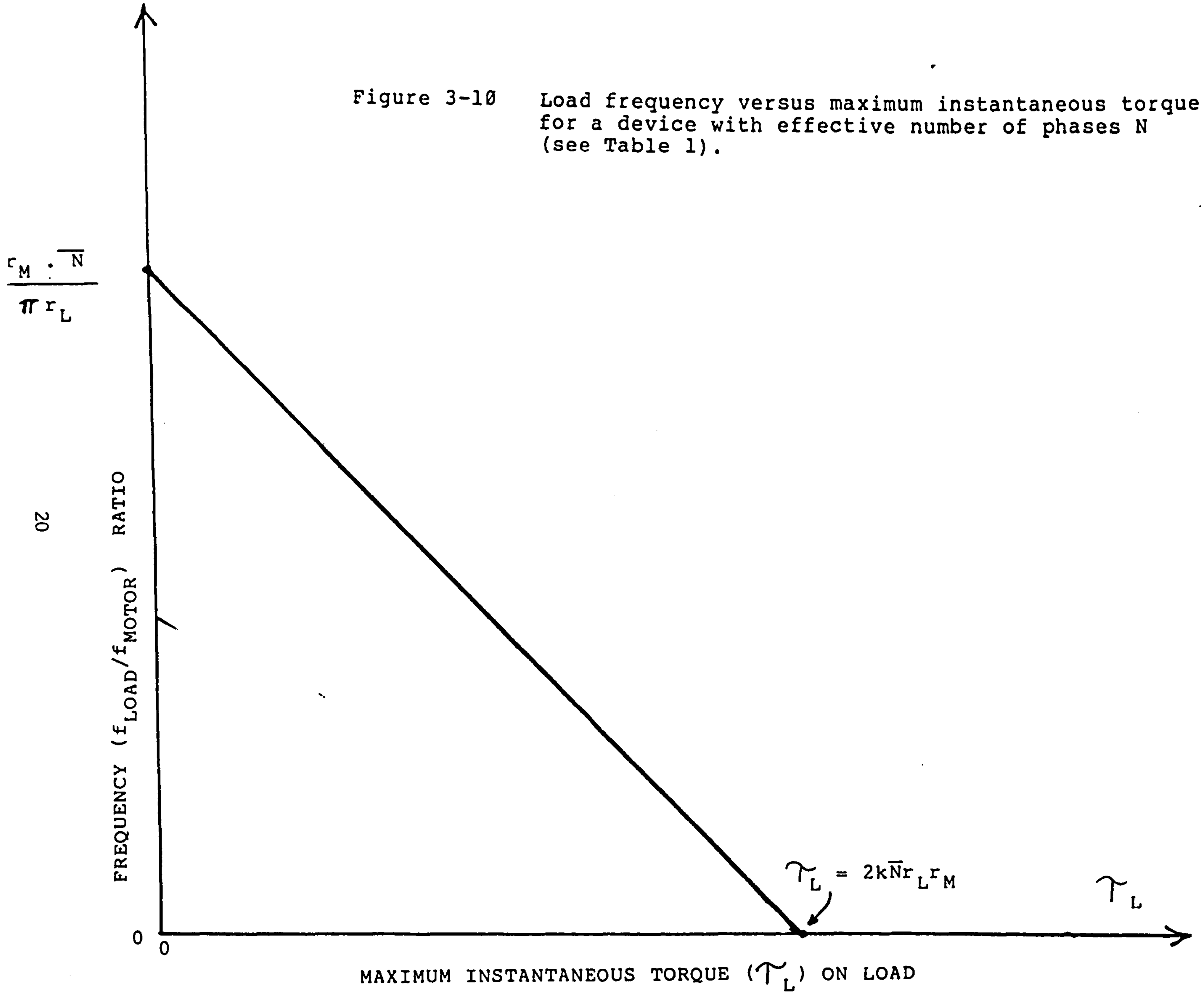

Figure 3-10 Load frequency versus maximum instantaneous torque for a device with effective number of phases N (see Table 1).

The average power delivered to the load can also be calculated from the torque T at which the springs stop stretching. Some simplifying assumptions lead to the following evaluation for the average power delivered to the load:

$$P = \overline{N} \cdot T_L \cdot w_L \left[(\pi - 2\Theta')/2\pi \right] , \tag{8}$$

where Θ' is the angle or time variable at the instant that the spring force becomes sufficient to move the load. The value of Θ' can be found from examination of plots showing the output velocity for a given T_L (see Figs. 3-3, 3-8, or 3-9). Fig. 3-11 shows the output torque in inch-ounces, versus the output frequency (in revolutions per second) for two values of average power (in Watts). For purposes of conversion, it may be useful to note that 1 ft - lb = 192 in-oz, and 1 in-oz/sec = 0.007 Watts.

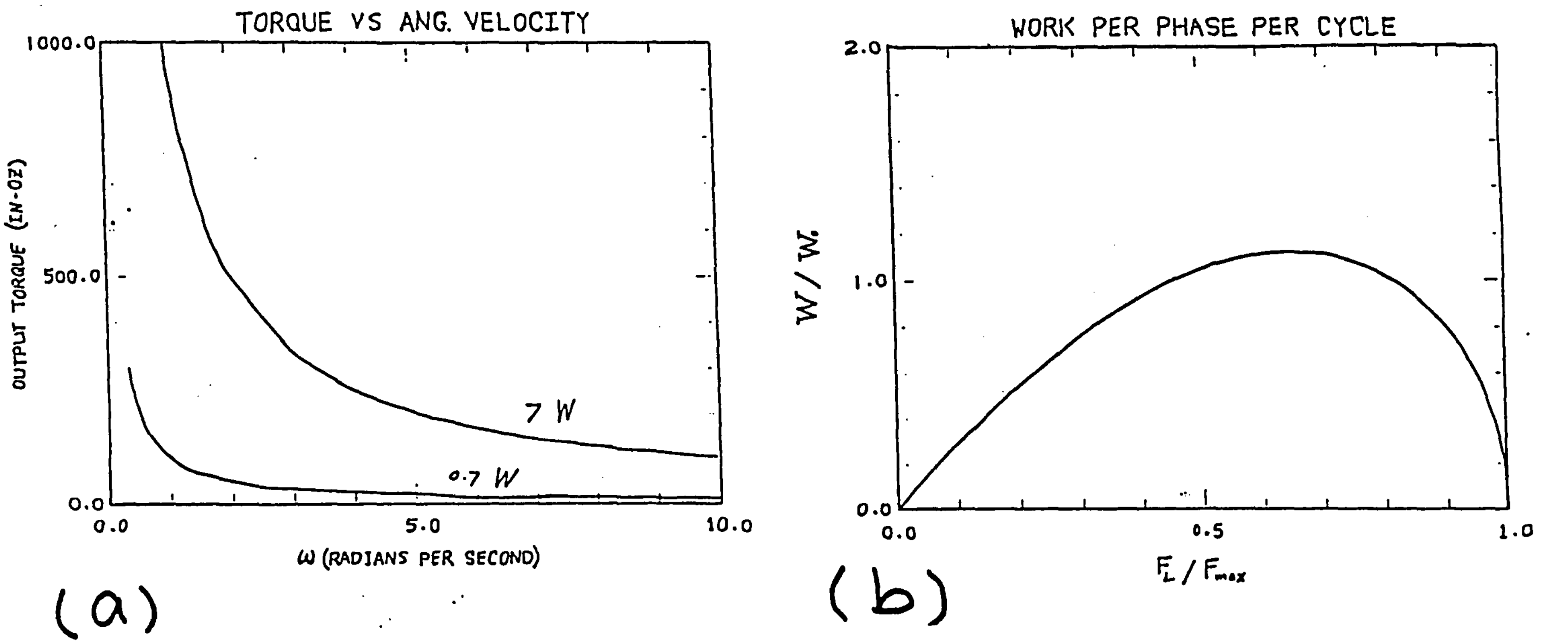

Fig. 3-11 Theoretical plots: (a) Output torque vs output angular frequency for two average power values of 0.7 and 7 Watts, assuming that the work per phase per cycle is near constant, and (b) graph of the work per phase per cycle as a function of the force F_L needed to move the load (relative to the maximum spring force available). W_o is maximum work obtained in a one radian rotation of the load.

4.0 PROTOTYPE DEVICE DEVELOPMENT

Fig. 4-1 shows a schematic drawing of the general concept for the off-axis version of Amjadi torque convertor. In this drawing, the device shown has 3-phases, but in general, any number of phases N can be employed. The fundamental characteristics of this version of the device are the following:

a. The input shaft is a crankshaft with the angular separation of the cranks being 360 degrees/N.

b. The linkages between the input and output shafts are springs.

c. One-way clutches on the output shaft deliver power to the load in N sequential phases.

The prototype device that was designed and built for this program is similar to that shown in Fig. 4-1, except that it has five phases, the separation between the input and output shafts is adjustable, and it is equipped with return springs on the one-way clutches (see Fig. 3-4). Table 1 shows a summary of the nominal design specifications for this model, designated Model 5FX.

Figs. 4-2, 4-3, and 4-4 show photographs of the actual Model 5FX test device. This device was evolved over a period of time. Its integral parts remained the same, but many of its peripheral features such as the return springs, mechanical couplings, and the particular drive springs (see Table 1) were changed. The actual layout was also changed to accommodate test instruments, a pulley at the output, and adjustment mechanism for the return springs. The test instruments included tachometers on the input and output shafts, and mechanical scales that were occasionally connected to test the tension in the springs.

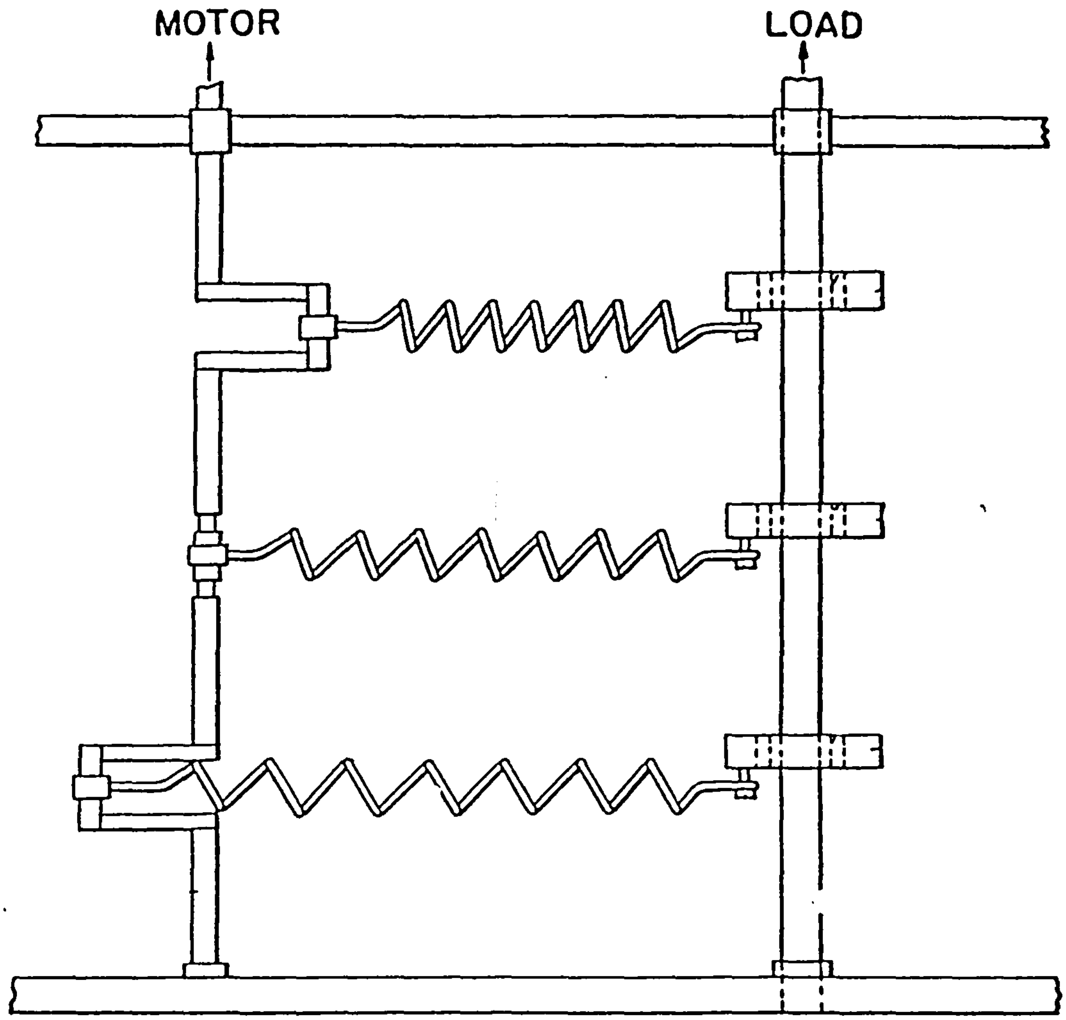

Figure 4-1 Schematic drawing of the off-axis version of Amjadi torque convertor, showing the basic components.

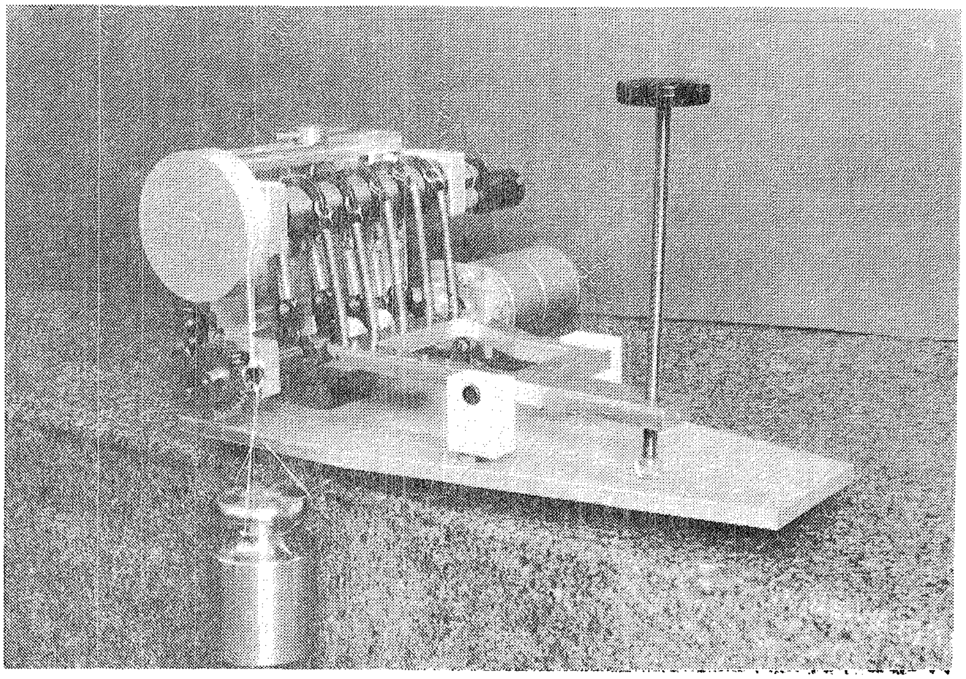

Figure 4-2 Photograph of the test model 5FX showing the overall apparatus. The spring linkages, the output pulley, and the long adjustment screw for cntrolling the tension in the return springs can be seen. The small handle on the upper left hand side is for changing the operating point of the drive springs by controlling the shaft separation.

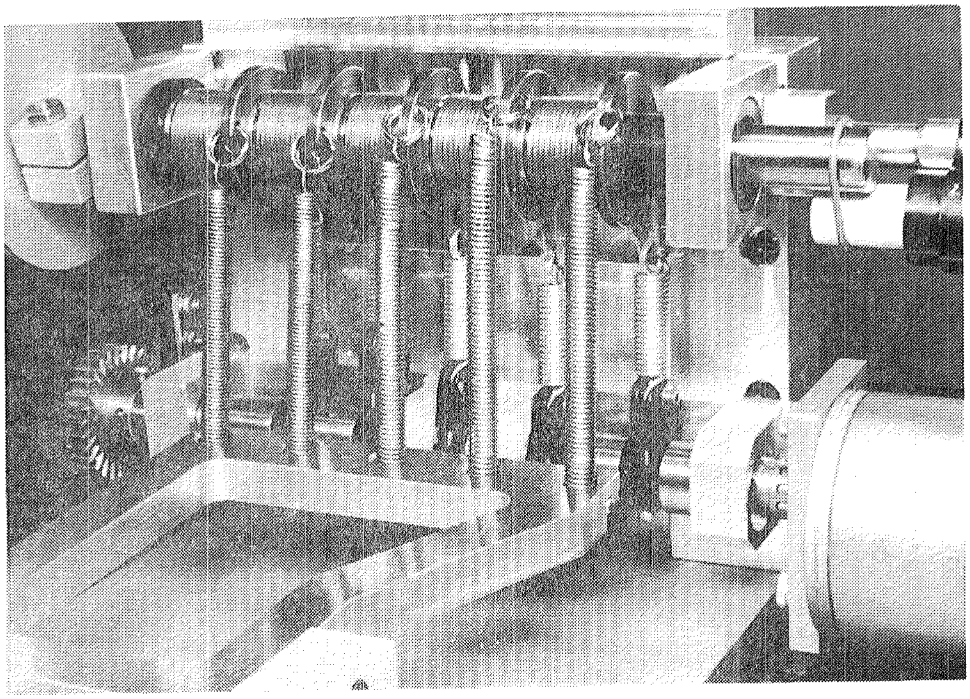

Figure 4-3 Photograph of Device 5FX, showing the wrap-spring one-way clutches (seen around upper horizontal shaft), drive springs (the shorter set), and the return springs (the longer springs in front).

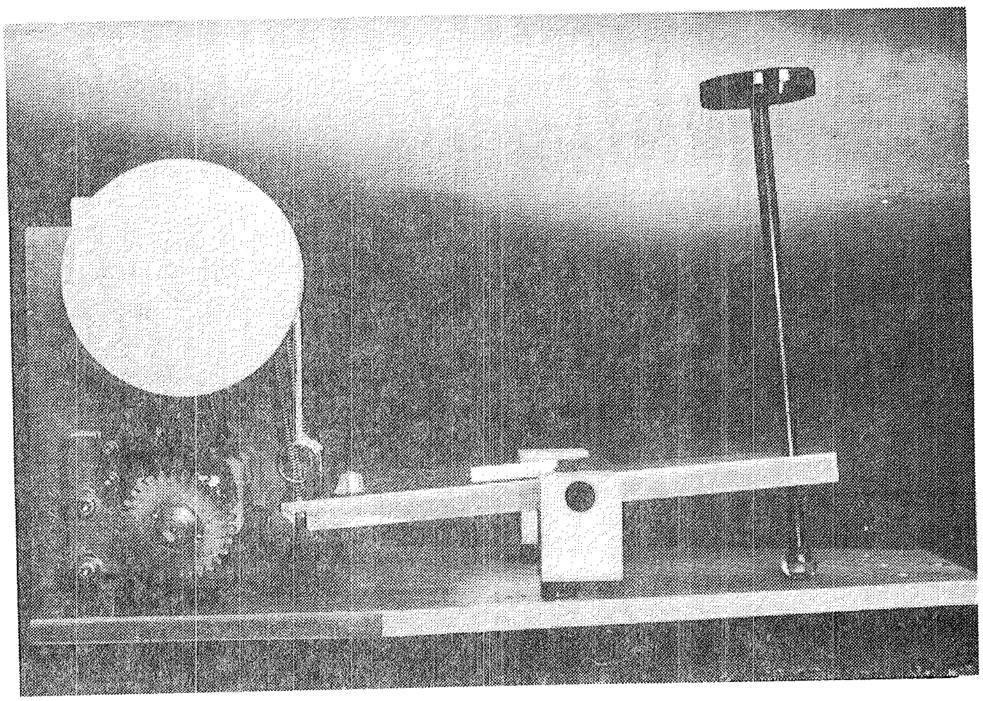

Figure 4-4 Photograph of Model 5FX showing the adjustment screw for tilting a plane which controls tension in all five of the return springs.

TABLE 1
DESIGN SPECIFICATIONS FOR MODEL 5FX
PROTOTYPE TEST DEVICE

NUMBER OF PHASES (N)	5
DRIVE LINKAGES	Extension springs Force Constant = 25 lb/in Length = 1.37 in Starting Force = 2 lbs
RETURN SPRINGS	Extension Springs; Tension for all can be adjusted with one adjustment screw Force constant = 1.25 lb/in
MOTOR DRIVE	DC motor with 50-to-one gear reduction
INPUT SHAFT	Crankshaft (5 cranks); Crank radius = .218 in
OUTPUT SHAFT	Directly driven by the one-way clutches. Pully Radius = 1.15 in.
ONE-WAY CLUTCHES	Wrap-Spring Clutches Maximum reverse torque = 1000+ in-lb Lever arm (r) = .55 in
INPUT/OUTPUT SHAFT SEPARATION	Adjustable (between 1.2 and 3.5 inches)
OUTPUT COUPLER	Adaptable to pulleys for fixed torques or to couplers for hookup to conventional tools
OUTPUT TORQUE	Automatically determined (see Eq. 5) between near zero and a max. value. Maximum instantaneous torque can also be adjusted by the tension in the return springs (See Sections 4.2.1 and 4.2.2)
OUTPUT VELOCITY	Average value automatically adjustable by the load torque requirements (see Eq. 5) between zero and a maximum value (See Section 4.2.1)

Since a properly hardened crankshaft was not available, a prototype unit was designed using disks and rods, and constructed. Its deficiencies became known near the end of the program after the device tests were extended to using stronger drive springs.

4.1 Important Features of Model 5FX

1. The main drive springs allow direct input/output coupling with automatic control of output-to-input gear ratios (see Figure 4-3).

2. The device can operate indefinitely (if necessary) at zero output velocity, while maintaining a high torque on the load.

3. Effective gear ratios vary continuously.

4. Input-output shaft separation can be varied to accommodate different sets of drive springs, or to change the operating point of a given set.

5. Return springs were later added which could reset the drive springs (see Fig. 4-3), and allow adjustments (see Fig. 4-4) of the applied output torque.

The operation of the device was tested by applying different voltages to the drive motor, and simulating various load conditions by hanging weights from the pulley at the output.

4.2 Performance Tests on Model 5FX

Operating characteristics of the 5-phase device were examined in terms of the output torque, velocity, dynamic range, power transfer, and independent torque control. It was found that the characteristics were in agreement with the general expectations based on the generic device properties. Device properties were also examined in connection with how they might be employed in tools or robotics, and what improvements would be needed to improve the device for such applications.

4.2.1 Output Torque and Velocity Measurements

The output shaft of the device was fitted with a pulley to allow fixed forces (torques) to be applied to the device load shaft. Fig. 4-5 shows plots of the output torque versus average output velocity for several motor voltages. As expected from the properties of such a device, where power flows through spring linkages, the output torque depends inversely on the (average) output velocity. The proportionality constant is the power being transferred, which in turn, depends on the power applied to the motor (see Eqations 5, and Fig. 3-11).

Comparisons between modeling studies and the experimental results indicated close agreement in terms of the general behavior. For example, the load torque could be abruptly changed from low to high values, and the device would respond immediately by changing the effective gear ratios, i.e., the output velocity would decrease and the output torque would increase to match the load demand.

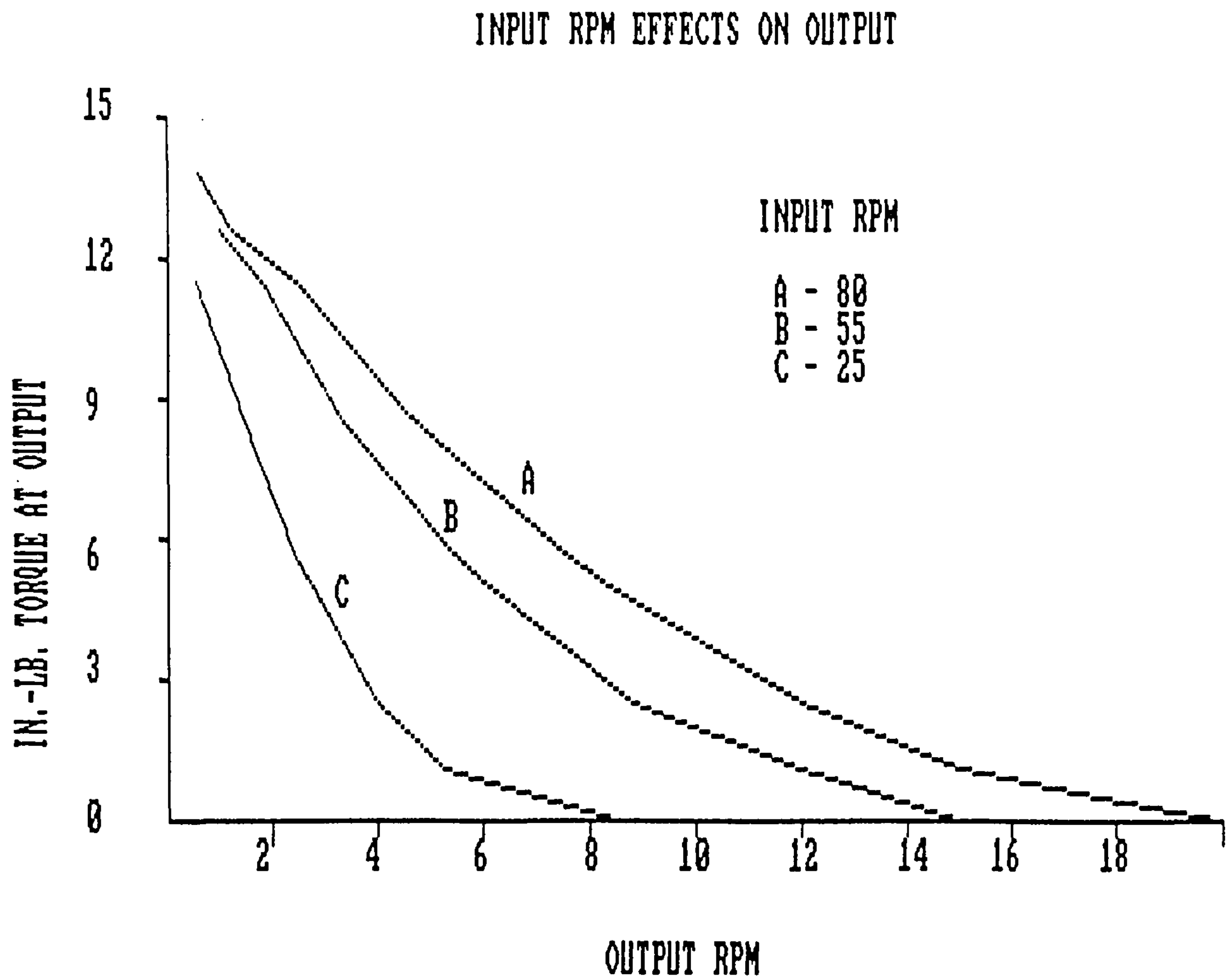

Figure 4-5 Plots of output torque versus average output (angular) velocity for Device 5FX for different values of motor voltages.

The response time of the device can be nearly instantaneous, so long as one of the drive springs is exerting a force onto the load at the instant that the load change is occurring, and the direction of the load change is such that it can be accommodated by the spring as the cycle proceeds. If the load conditions and the load change are such that an immediate response is not possible, the torque response will occur at the instant that the next drive spring begins to exert force on the load. In such cases, the response time has an upper bound of

$$t = 1 / (2 N f_L),$$

where f_L is the frequency of rotation of the motor shaft, and N is the number of phases. Therefore, delayed response is likely to be observed with devices with few (i.e., $N < 3$) phases. For torque convertors with $N = 3$ phases or more, the response time is likely to be very short, and in any case, less than t. For Model 5FX, for motor shaft rotation rate of 1 Hz, the response time is less than 0.1 sec, and in the majority of cases considerably below this value. Our experimental (qualitative) observations are in excellent agreement with this conclusion.

We have discussed earlier (see Section 3.2) the fact that the output velocity of the torque convertor in some circumstances becomes pulsed. This occurs whenever the drive springs have to stretch to a large degree to move the load, such that the overlap of successive phases is lost. Then each drive spring essentially acts alone. The larger the number of phases, the larger the range of torques that can be handled before the output velocity changes from continuous to pulsed operation. In general, however, this torque convertor should be considered as a pulsed power transfer device. Fig. 4-6 shows the output

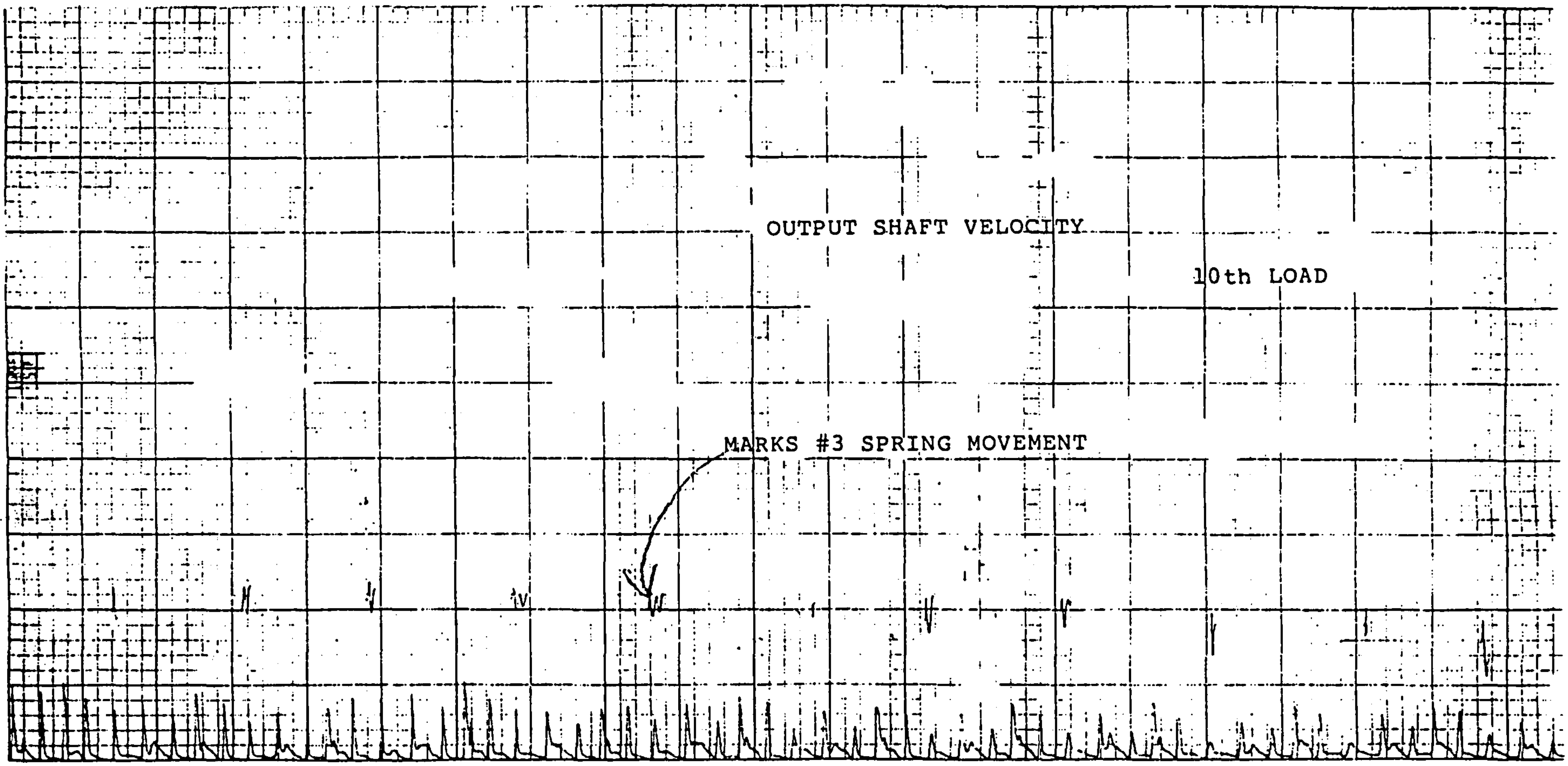

Figure 4-6 Experimental observation of the pulsed (square wave) output velocity of Model 5FX, while lifting a 10 lbs weight. The signals are obtained by using a motor as a tachometer, which produces the largest signals at the start and stop of each pulse (derivative signal).

velocity of Model 5FX while it is lifting a 10 pound load. The pulsed power delivery (square waves, similar to that shown in Fig. 3-8(b)) is observed by the derivative signal measured on a small motor used as a tachometer. Pulses are generated once at the start, and once at the stop of the square wave output velocity profile.

We have tested the system response to a stalling load force. As expected, a maximum average torque remains on the load for as long as the condition persists, but the motor continues to turn without any adverse effect due to the stalled load. The power consumed by the motor also drops, since the applied torque does not do any work on the stationary load. Direct application of the same stalling torque (or even much less) directly to the motor shaft, however, causes immediate problems, and cannot be done for more than a few seconds without overheating the motor. Therefore, it is obvious that the torque convertor can do an excellent job of dynamic "impedance" matching the motor to the load, under a variety of load conditions, including the extreme case of a stationary load.

4.2.2 Dynamic Range

The dynamic range of spring-driven devices such as our Model 5FX is dependent on the force constant of the springs, the initial tension (if extension springs are used), as well as device parameters such as the shaft radii r_L, r_M (as defined in Section 3 above), and the shaft separation.

4.2.3 Power Transfer

Operating characteristics of the device in terms of mechanical and electrical power were studied and compared with theory. Fig. 4-7 shows the motor current measured for input

voltages of 15 and 21 volts. In each case, the measurements are shown for the conditions of no load (minimum output torque, maximum output velocity), and complete stall (maximum torque, zero output velocity). These are both cases where the system is not doing useful work. Therefore, the slight increase in the average current in going from no load to stall condition represents the increased losses due to imperfections in the system construction. For example, we know that the motor crankshaft, which is held at several locations between the cranks in simple bushings, experiences increased friction when the drive springs come to full stretching under the stall conditions, and apparently deform the crankshaft slightly.

The larger current noise for the 15 volts input case in Figure 4-7 is due to the fact that the electric motor is designed for operation at more than 20 V. The oscillations in the current under stall conditions are due to the periodic deformation of the drive shaft, as mentioned above. The current spike that occurs on application of a load stall condition represents the additional energy that becomes initially stored in loading the drive springs. This is a regenerative process, and the excess energy stored in the drive springs goes back to the motor when the load requirements are reduced. Small negative spikes in the motor current which indicate power return can be seen better in Fig. 4-8 at start of a free run after a stall period. The larger oscillations in current, as compared with Fig. 4-7, are due to stronger drive springs (and the problems mentioned above with the crankshaft).

4.2.4 Torque Control

As we discussed earlier, a special feature included in Device 5FX was torque control via a set of return springs (see

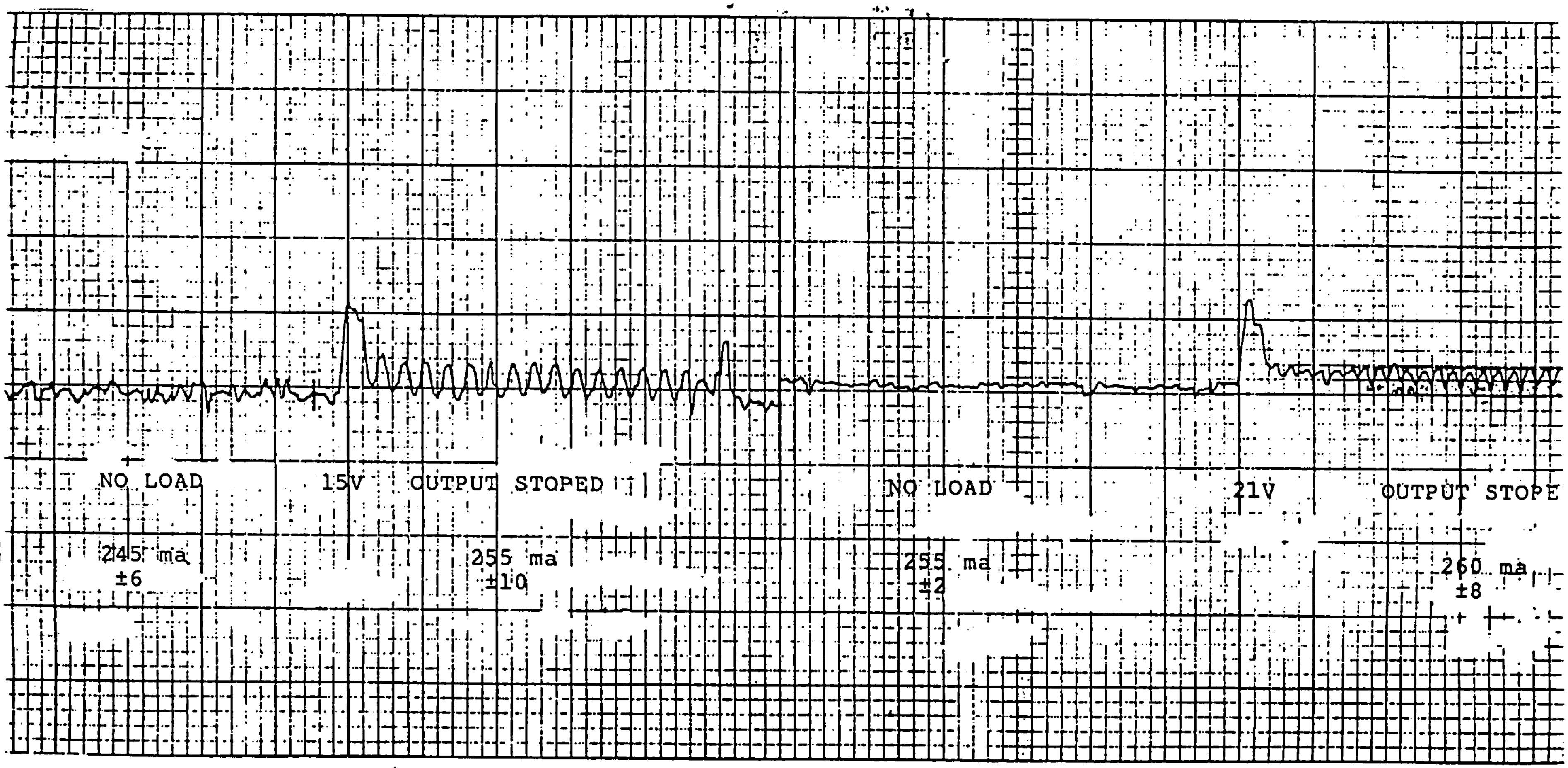

Figure 4-7 Experimental plots of the motor current versus time for input voltages of 15 and 21 volts, for the cases of no load and stall condition (i.e., maximum output torque, zero output velocity).

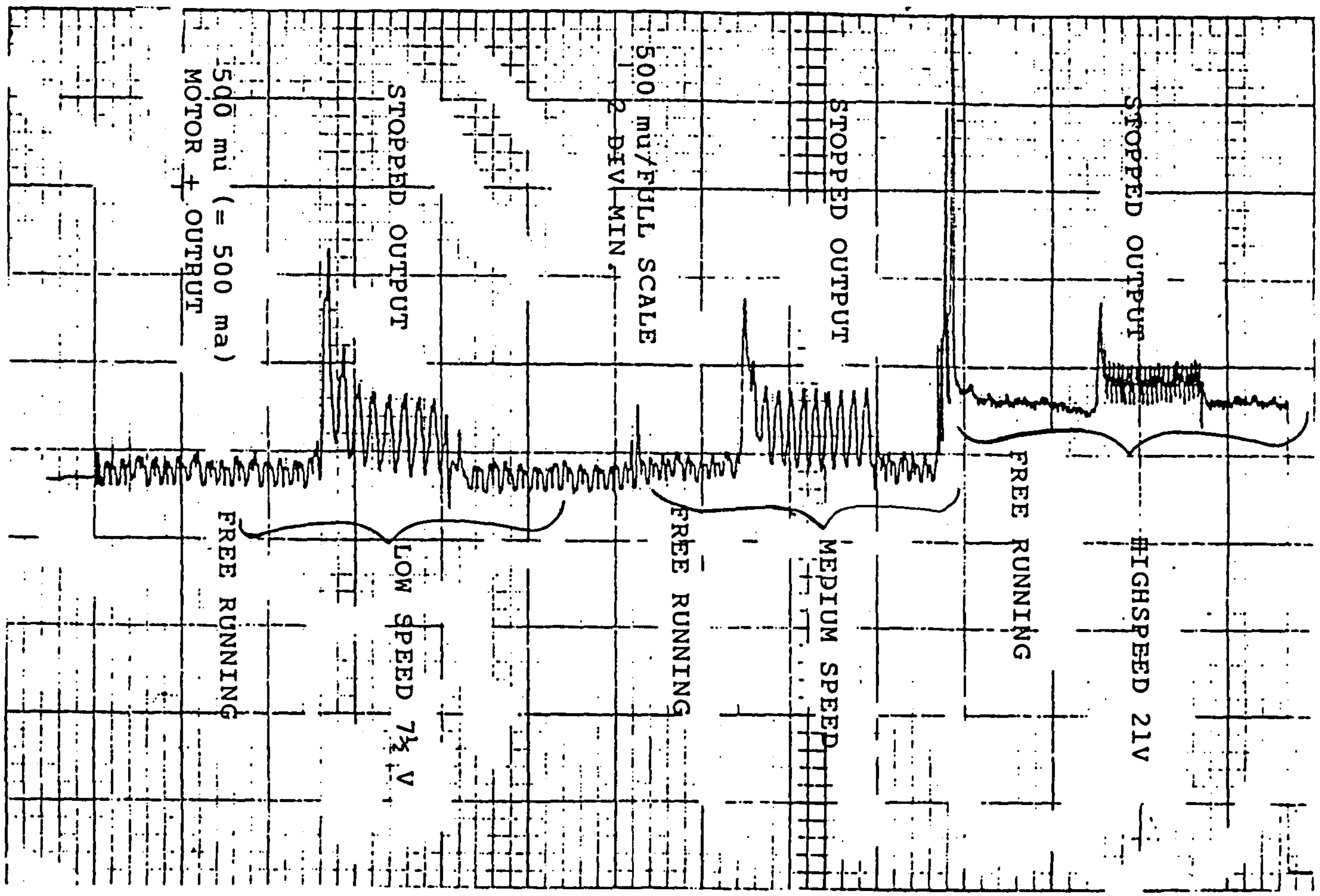

Figure 4-8 Plot of motor current for a variety of motor voltages, (7.5, 15 and 21 V), for the cases of free running and stalled conditions. The drive springs here are stronger than the case shown in Fig. 4-7.

Fig. 3-4). These springs were originally used for returning the one-way clutches to the starting point, so that extension (instead of compression) drive springs could be used. Since the drive springs are of the extension type, a minimum tension is required in the return spring, before the one-way clutches are properly reset in each cycle. This minimum tension varies with the maximum stretching of the drive springs in each cycle, i.e., with the load (see Fig. 4-9). However, beyond about 0.5 pounds, the required value saturates. This is related to the maximum load capability of the drive springs and the given value of their maximum stretch ($2r_M$). If the tension in the return spring is increased further, it will offset the maximum output torque of the device, as shown in Fig. 4-10. Therefore, for a given output velocity, the output torque can be controlled.

The torque control achieved in this way is regenerative, i.e., no power is dissipated. The net effect of the return spring is to yield an effectively lower spring constant for the drive springs. Alternatively, its effect may be viewed as an effective reduction of the drive spring extension amplitude ($2r_M$).

Successful implementation of this approach was motivated by our desire to have the option of independent control of the maximum torque. The device can then automatically control torque up to that maximum value. This is a useful additional capability for an advanced torque converter, especially for tool applications, or for applications such as valve actuators where torque-limiting may be required.

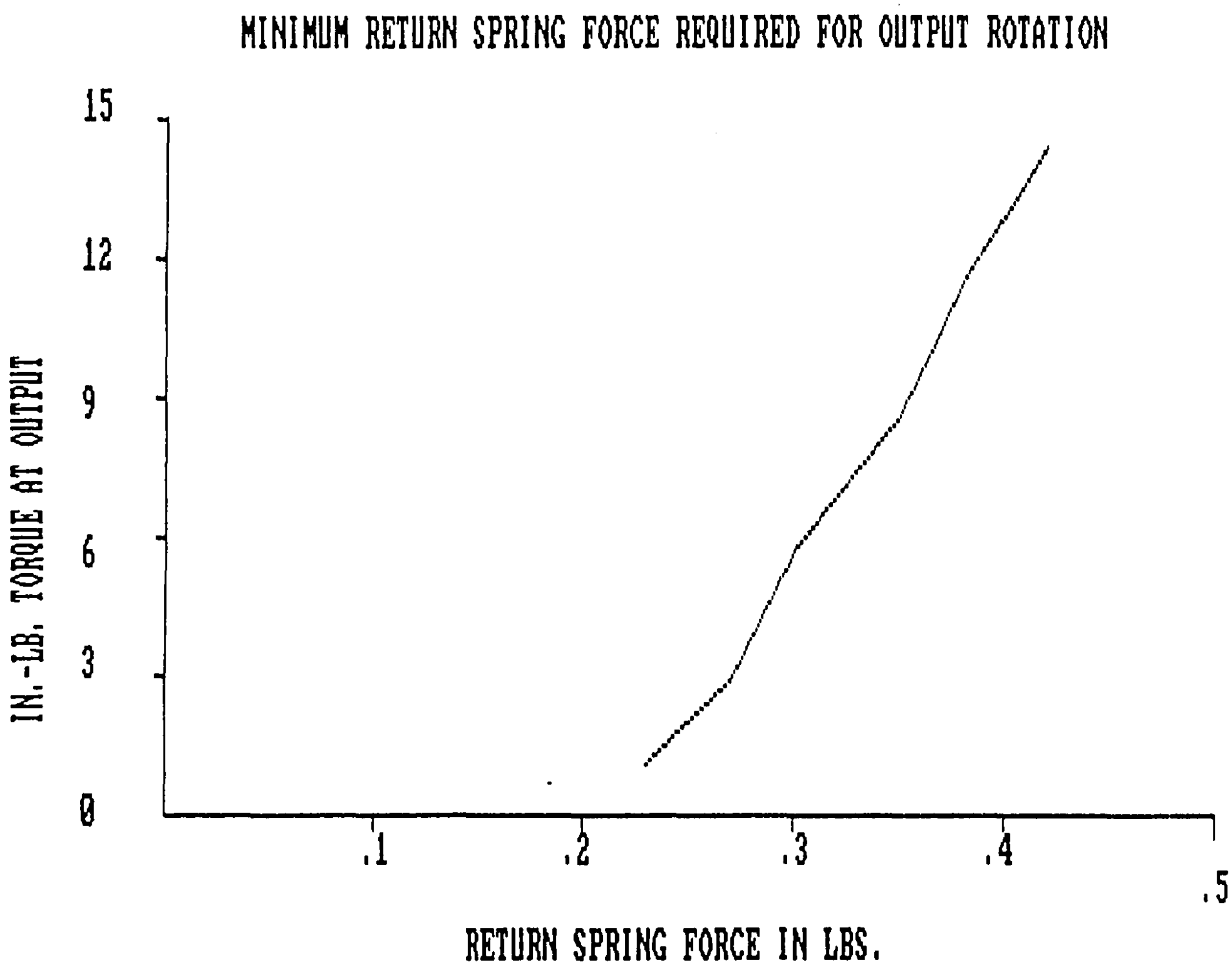

Figure 4-9 Plot of the minimum required force of the return spring versus the maximum lifting force desired (the radius of the load pulley = 1.25 in.).

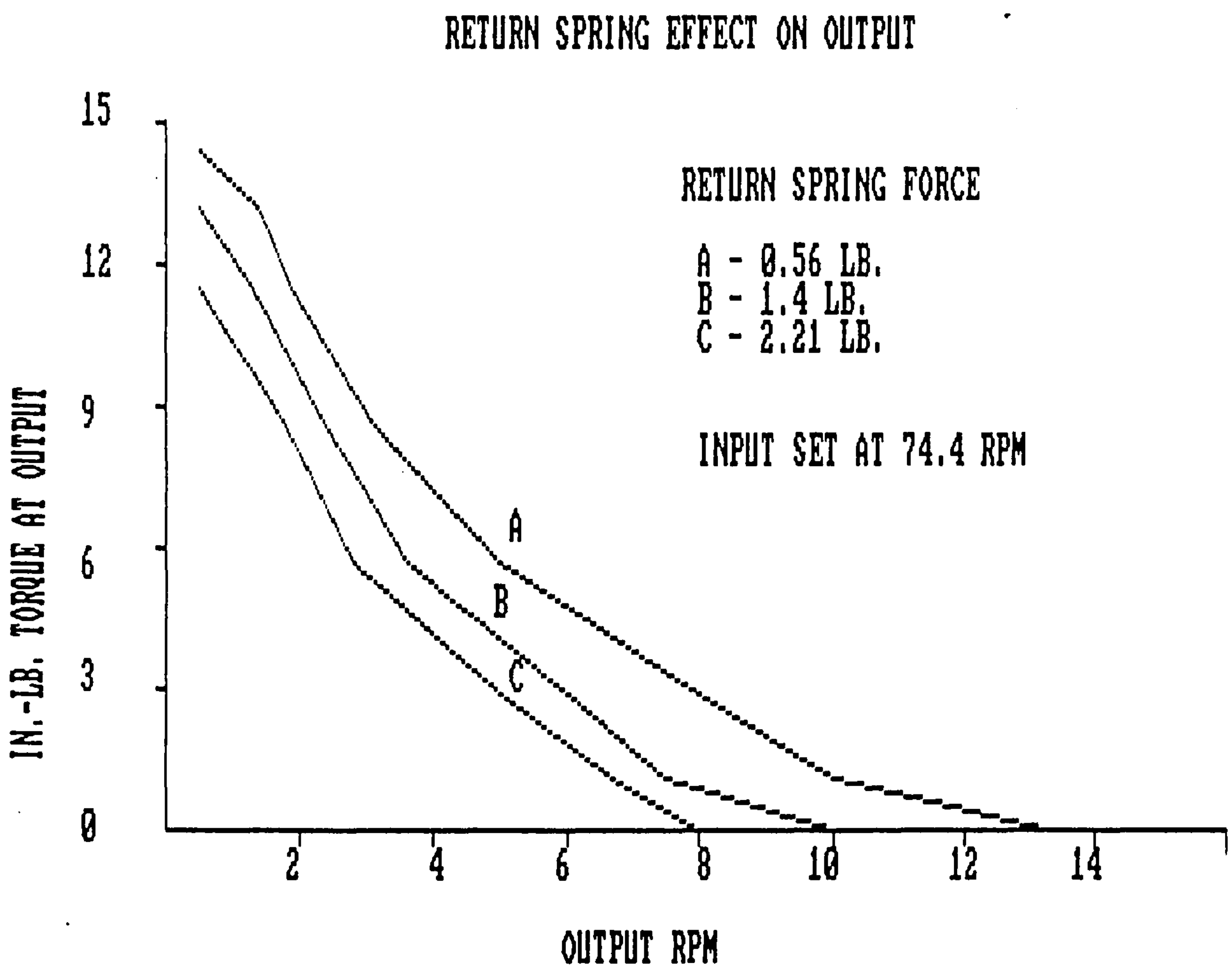

Figure 4-10 Plots of output torque versus output velocity for a number of tension settings on the return springs, showing how different torques may be obtained for a given output velocity (motor voltage = 20 V).

4.3 Prototype 3-Phase Device (Model 3NX)

A three-phase, on-axis device (Model 3NX) was designed and developed which is quite different from the test device described above. Its important characteristics are listed below:

1. It employs three phases, and the input/output axes are along the same line. Wrap-spring clutches are used as one-way clutches.
2. Drive linkages are rigid rods.
3. Automatic operation is achieved by making the effective radius r_M of the pivot point on the motor drive (Point A in Fig. 3-1) variable.
4. Zero output velocity is achieved by allowing the pivot point to move over the center (i.e., $r_M = 0$).
5. The flexibility, and the regenerative aspect of the automatic torque ratioing, are provided by a return spring which tends to always increase r to its maximum, if the load torque requirements permit.
6. The device is made fairly small, suitable for demonstrating its application as a tool driver.

Fig. 4-11 shows a schematic drawing of the on-axis, 3-phase version of Amjadi Transmission with rods as linkages, as it appears in the original patent. The ratchets shown in this diagram can be any type of mechanical diode, e.g., wrap-spring clutches. Here, the specific mechanism for changing the radius of the pivot point on the drive shaft is not shown because there are numerous options available. For example, a flexible cable can be used to change this radius, and obtain a manual transmission, but with smooth ("infinite gear ratio") adjustment of the torque ratios. Automatic operation may be achieved by schemes such as centrifugal action or spring-driven movement of the pivot point by a folded arrangement of linkages which can swing the pivot point over the center of the disk.

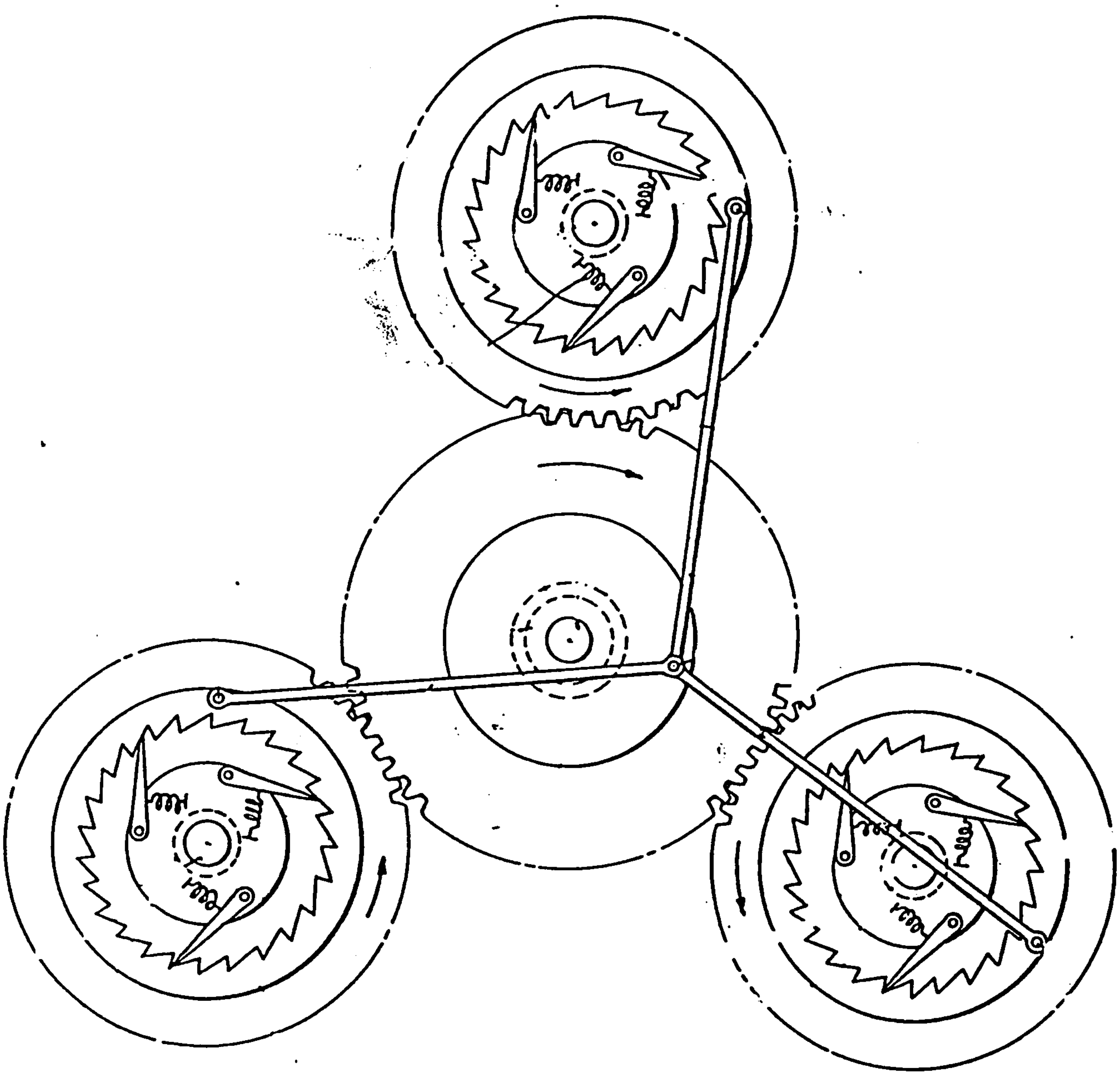

Figure 4-11 Schematic diagram of the 3-phase on-axis torque converter. The mechanism for changing the radius of the pivot point on the contral drive disk is not detailed here. The load drive is via the larger gear which is coaxial with the motor driven shaft.

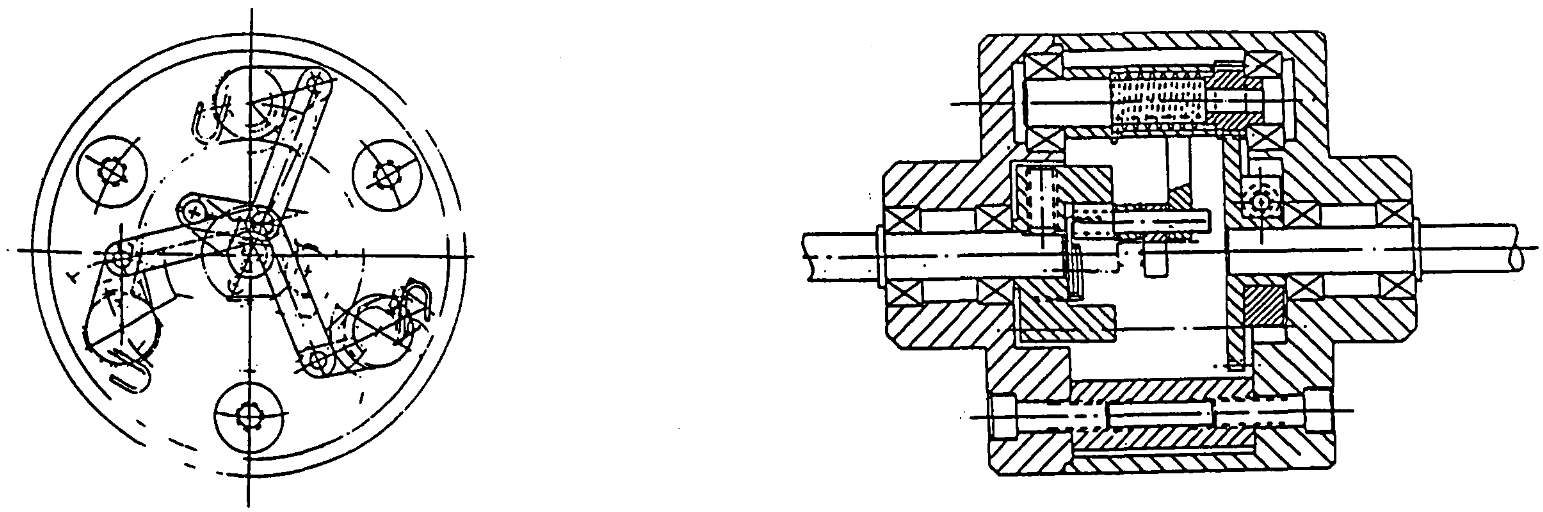

Figure 4-12 Technical drawings of the top view (left) and side view of Model 3NX. Note the three rod linkages extending out from the pivot point, and the folded linkages between the center and the pivot point.

An important requirement for all such mechanisms is the ability to zero the radius ($r_M = 0$). This condition is necessary so that the device can tolerate the extreme mismatch of a stalled load and a running motor, which is to remain unaffected by the stall condition. Fig. 4-12 shows technical drawings of the actual device that was built. The top view (left-hand side) shows the folded arrangement of linkages that can move the pivot point all the way to zero radius under heavy torque demands.

Fig. 4-13(a) is a photograph showing a perspective of Model 3NX, and Fig. 4-13(b) shows the two halves of the device. Fig. 4-14(a) and (b) are photographs showing details of the inner components.

The operation of Model 3NX has not been examined in as much detail as the earlier test model, except that we have verified that it operates very well. The input shaft was held in a chuck of a drill press, and output shaft was connected to variable loads. In a simulation of the application as a tool driver, this torque converter can be connected directly to a motorized driver, presumably suitable for space applications. To date, the tests on this device have been primarily qualitative. The general characteristics of Amjadi torque converter, however, are all successfully demonstrated in this device, i.e., automatic control of output torque and velocity, high torque and low loss for zero output velocity, and torque-limited output. In its present configuration, the device produces a 10-to-1 gear reduction with no load, and can be loaded to a full stall without any adverse effects on the electric motor.

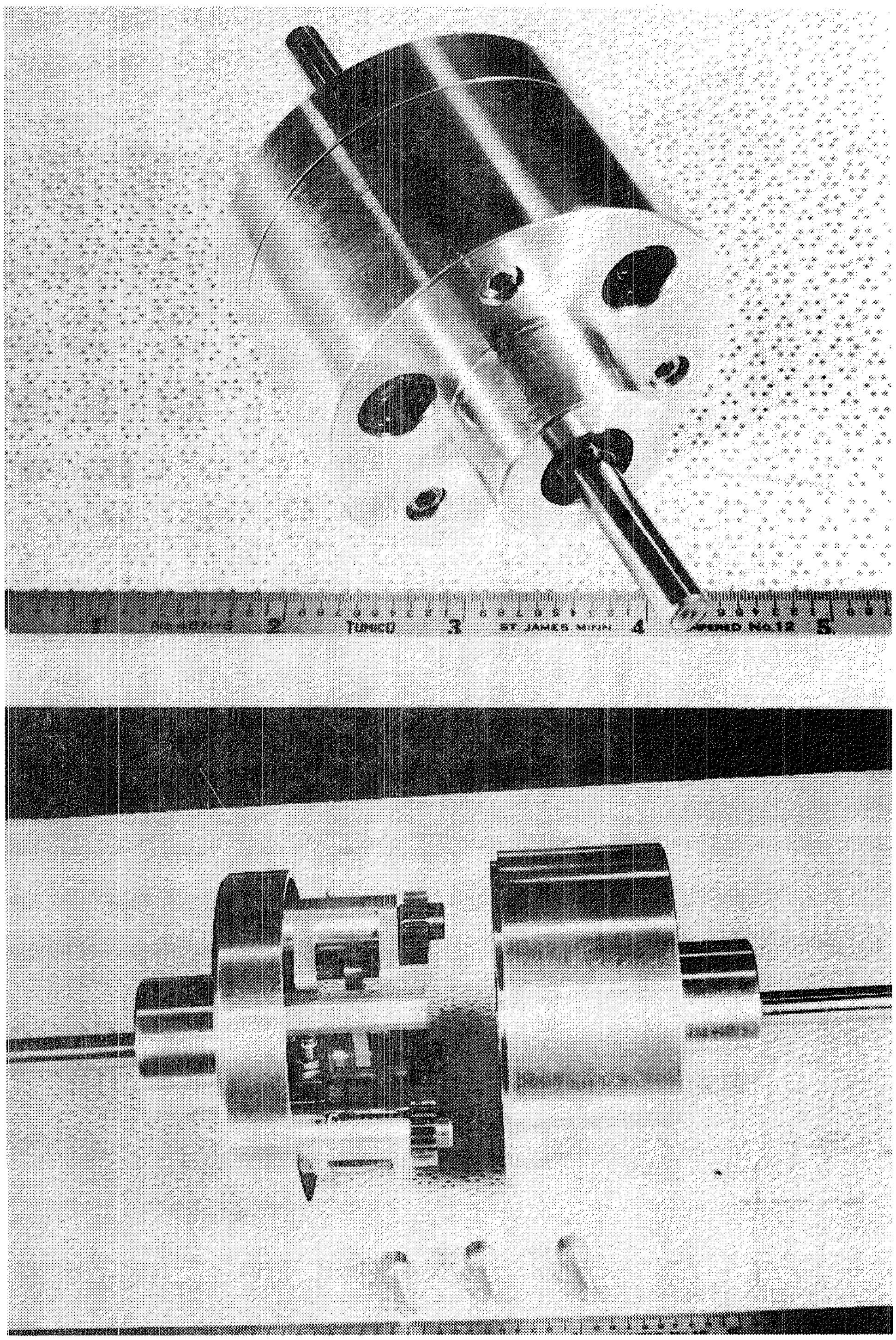

Figure 4-13 Photographs of Model 3NX showing the general view of (a) -upper photo, the complete device (note the scale), and (b) -lower photo, a view of its two major components. Input shaft and the transmission parts are all mounted on the same flange.

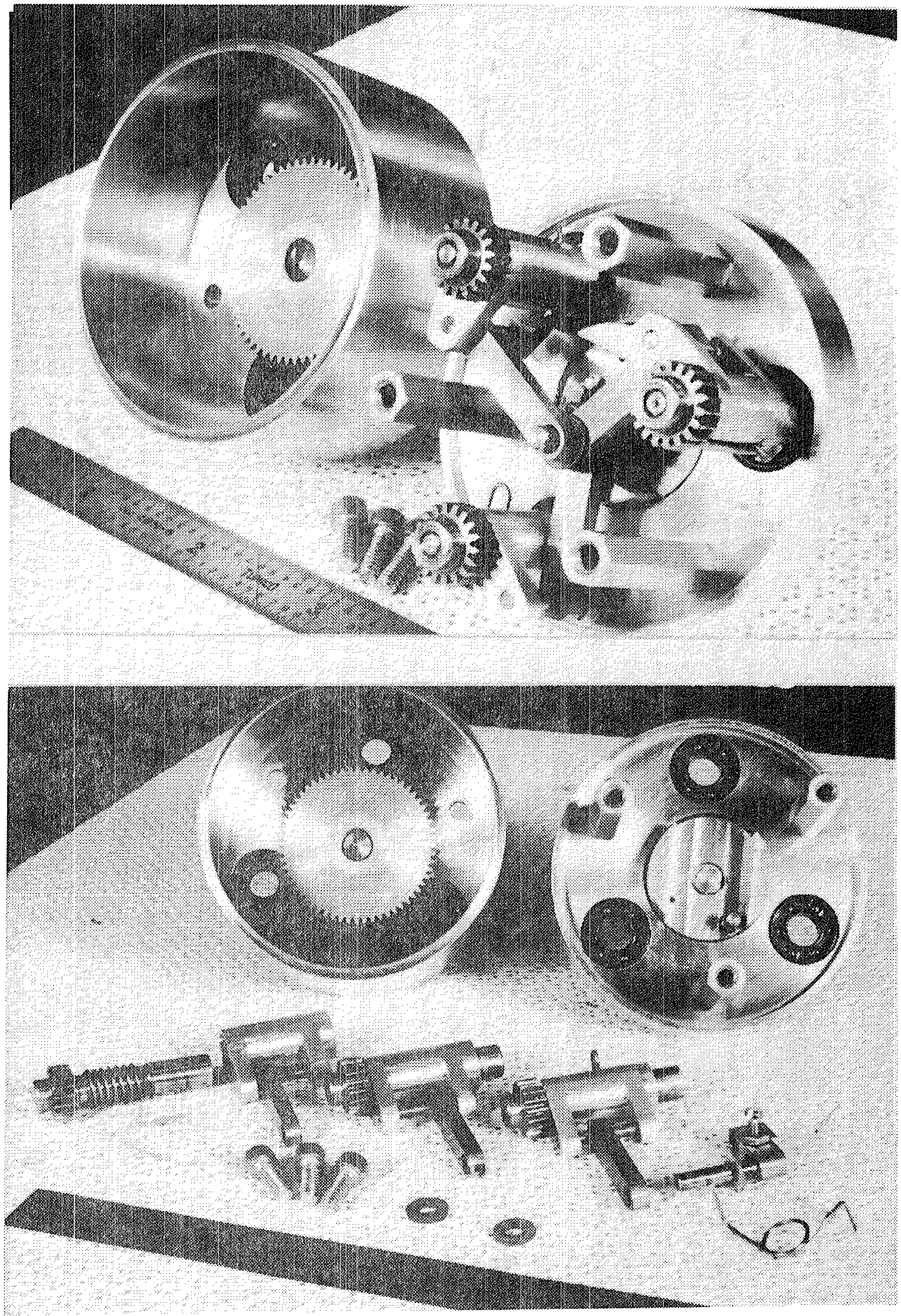

Figure 4-14 Photographs showing details of the inner components of Model 3NX. In both photos, the input half is on the right hand side. In the upper photo (a), the torque converter parts are still assembled. In the lower photo (b) they are exhibited. The torsion spring in lower right of (b) is the main return spring.

5.Ø APPLICATION ANALYSIS

The issue of identifying potential applications of the torque converter has been a primary one for this program for two reasons. First, the applications influence design parameters. Second, future success of this Phase I effort in securing investments, or committments for a future phase of NASA SBIR program, depended on applications and a commercial market base. Therefore, we embarked on determining the types of space tools and robotics applications that would be of interest to NASA, and evaluation of their wider base of potential commercial market. In this endeavor, as well as with some design and analysis tasks, we had collaborations with Trans-Kinetics Corporation of Newbury Park, California, of which A. Amjadi (the inventor of the main concept) is a principal. This company is currently developing applications concepts other than tools and robotics for the torque converter, primarily vehicular.

Exploratory studies were carried out, using the documentation [1] that was found available on space tools of interest to NASA. A survey of some up-to-date material on robotics [2] was also carried out. The applications analysis also considered some device-related issues which influence applications, as briefly described below.

1. "Shuttle EVA Description and Design Criteria, "Final Report, Repot No. JSC-1Ø615-REV-A, May 1983, Available through NTIS.

2. See, for example, "Robot Hands and the Mechanics of Manipulation," M.T. Mason, and J.K. Salisbury, MIT Press, 1985.

5.1 Device Related Applications Issues

Three device related issues were found to have major influence on applications. They include the one-way clutches, materials, properties and packaging.

5.1.1 One-Way Clutches

There are a variety [3] of one-way clutches that are currently available, some active, e.g., magnetic clutches, but mostly passive. We examined a number of them for our application in terms of the following parameters:

1. Large reverse torque, with minimum backlash.
2. Low starting friction and high energy efficiency in the forward direction.
3. Ease of reversal in direction of operation.
4. Small size and weight.

Our conclusion was that, for applications where reversibility is not an issue, wrap-spring clutches [4] are the best candidates. Ratchet mechanisms were found to be the simplest to reverse, but they are usually noisy and have backlash problems. We also devised a variation to the grip-roller freewheeling clutches which should allow reversibility, but this has not yet been implemented.

3. See, for example, an impressive list of products in Thomas Register on "Clutches".

4. "A New Twist in Overrunning Clutches," Design Engineering, pp 54-57, Nov. 1980.

5.1.2 Materials and Packaging

The issue of materials can greatly influence the reliability of a mechanical device such as the torque converter, and the issue of packaging is directly related to the intended applications. Only limited consideration was given these issues during the course of the program because of more preliminary issues that needed to be addressed. The packaging and selection of materials for Model 3NX described above were based on these considerations. However, detailed tests to examine extended operation and determine useful life of the Key components were not carried out. The earlier versions of Model 5FX were subjected to long continuous runs (many days), to "burn in" the various components; no failures resulted from these tests.

5.2 Applications

Two broad areas of applications were examined for the torque converter within this effort. They included tool drivers and components related to robotics.

5.2.1 Tool Drivers

Examination of the generic tool drivers that could benefit from the torque converter concept revealed a variety of such potential applications. Examples include screwdrivers, nutdrivers, impact wrenches, modified rivoting tools and even valve actuators. Our conclusion here is that the unique properties of our torque converter, e.g., torque-limiting, automatic and continuous torque ratioing, etc., can truly enhance the operation of such tools, particularly for specialized applications iN space, where relatively few, but high performance devices may be needed. Our experimental data verified these general conclusions, but was not sufficiently quantitative to allow an accurate assessment of the commercial viability of these specialized tools.

5.2.2 Robotics

Application of our torque converter to several components related to robotics were considered. They included robotic actuators, end effectors, and active joints. The many interesting properties of our concept were envisioned to offer significant advantages. Numerous conceptual designs were developed and some real advantages were identified. We found these applications to be very interesting, but not free of problems. Two main areas of concern were also identified: first, achieving reversibility of operation; this required one-way clutches that could be easily reversed (see Section 5.1.1 above); second, the freewheeling nature of one-way clutches turned out to pose some difficulties. Neither of these problems were unsurmountable; however, in eliminating them, some of the advantages of our device would be compromised. The final conclusion here was that the application of our torque converter, in its present state of development, to robotic manipulators is probably not competitive. This conclusion does not apply to one application area, namely, robotic locomotion. Here, there appear to be some real possibilities that should be examined further.

6.0 PROGRAM SUMMARY

The following accomplishments can be cited for our Phase I effort, presented here in the approximate chronological order of achievement:

1. A study was made on the special needs of NASA in the areas of space tools and robotics. Despite the limited data that was available, attempts were made to align the program to address issues of interest to NASA, which might benefit from the capabilities offered by the Amjadi transmission concept.

2. The properties of the device were analyzed, and designs were conceived which could add to its capabilities in terms of:

a. External control of the maximum instantaneous output torque.

b. External control of the output velocity.

c. Alternative options for design of the on-axis model which can use rods as linkages.

d. Alternative designs for packaging the transmissions for robotics applications.

3. Theoretical modeling of the principles of operation of the general concept were carried out.

4. A study was made of the possible one-way clutches that could be used in construction of the Amjadi torque convertor. Wrap-spring clutches were found to be the most convenient; however, no easy way was found for making them reversible.

5. Various options for using the device in tools, space, and robotics applications were analyzed in terms of performance and limitations. A number of conceptual device designs were generated. The issues of economic competitiveness were examined.

6. A five-cycle torque convertor was designed and fabricated. The device is based on Amjadi transmission concept of the parallel axes model. It uses springs as linkages for energy transfer. It is equipped with measurement instruments and provisions for external control of maximum output torque. This device was examined as a generic prototype for tool applications.

7. A three-phase on-axis model of the transmission was designed, built, and preliminary tests were carried out to verify its operation. This model uses rods as linkages for energy transfer. This is a small scale device, demonstrating the suitability of the concept for miniaturization and tool applications.

8. Performance tests on the prototype devices further verified the predicted behavior of the Amjadi transmission in its smooth change of gear ratios all the way from zero to finite output speeds, with virtually no deleterious effect on the motor. We also verified that the output velocity automatically increases as the output torque requirements drop, keeping the average output power constant. The new features of wrap-spring clutches, external control of the maximum instantaneous torque, and successful operation of a small scale on-axis prototype were established.

Despite the above accomplishments, we were unable to secure committments for Phase III follow-on funding. We attribute this problem to the rather short duration of the program which did not allow for much "marketing" of the results of the program efforts, before a Phase II proposal had to be submitted.

7.0 CONCLUSIONS AND RECOMMENDATIONS

In this section, we outline our conclusions based on the results discussed above and discuss recommendations for future action. Our conclusions are as follows:

1. Models of two types of advanced torque converters

were designed and fabricated. These models allowed us to verify the most interesting features of the basic concept:

a. Automatic and rapid adjustment of the effective "gear ratio" in response to changes in the external torque requirements.

b. Maintenance of the output torque on the load even at zero output velocity, without loading the input power source.

c. Excellent isolation of input power source from the load even though they were direct mechanically coupled.

2. The devices are apparently suited to certain types of tool driver applications, such as screwdrivers, nutdrivers, and valve actuators, among others, as originally proposed.

3. Robotics applications have been evaluated and we find that, while there are many potential applications for this torque converter that must still be explored, its use for robotic actuators does not appear to provide sufficient advantages to warrant serious consideration.

4. The models developed for this program allowed us to make a qualitative determination of basic device properties. However, we were unable to obtain sufficient quantitative information to draw final conclusions as to the commercial viability of this device in tools and robotics applications. This conclusion was a key factor in our decision not to apply for a Phase II NASA SBIR program at this time.

We recommend that the areas of potential application for this torque converter are those which have the following characteristics:

1. The load torque requirements can vary widely or rapidly and it is desirable to maintain isolation between input power source and the load.

2. The load may stop entirely and it is necessary to maintain output torque without loading the input power source.

3. Application of output torque pulses is tolerable or desirable. An impact wrench is an example of such an application.

4. Torque limiting is required to avoid damage to an external part or to the tool itself, or is required to accomplish a certain objective.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-177987		

4. Title and Subtitle	5. Report Date
Advanced Torque Converters for Robotics and Space Applications	July 1985
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address Talandic Research Corporation 2793 East Foothill Blvd. Pasadena, CA 91107	11. Contract or Grant No. NAS1-17938
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code 324-01-00

15. Supplementary Notes

Langley Technical Monitor: Alfred J. Meintel, Jr.
Final Report

16. Abstract

This report describes the results of the evaluation of a novel torque converter concept. Features of the concept include: (1) automatic and rapid adjustment of effective "gear ratio" in response to changes in external torque (2) maintenance of output torque at zero output velocity without loading the input power source and (3) isolation of input power source from load. Two working models of the concept were fabricated and tested, and a theoretical analysis was performed to determine the limits of performance.

It was found that the devices are apparently suited to certain types of tool driver applications, such as screwdrivers, nut drivers and valve actuators. However, quantitative information was insufficient to draw final conclusion as to robotic applications.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Actuators Torque Converters	Unclassified - Unlimited Subject Category 37

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	59	A04

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